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Thermodynamics and performance analysis of a biofueled boiler energy system

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Thermodynamics and performance analysis

of a biofueled boiler energy system

by

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NOMENCLATURE

A1: subscript denoting wood energy system being evaluated

A2: subscript denoting fossil based energy system

A1:A2: subscript denoting the evaluation of wood energy system A1 relative to fossil based system A2

B_{A1j}: benefits (positive cash flows) in year j for the wood energy system (A1) being evaluated

B_{A2j}: benefits in year j for the fossil based energy system A2 against which wood energy system A1 is compared

BCR: Benefit/cost ratio

BEFF: Wood-fired boiler system efficiency

C: elemental carbon or weight fraction or percent of carbon in fuel, from fuel ultimate analysis

C_{A1j}: cost in year j for the wood energy system A1 being evaluated

C_{A10}: denotes cost of the system A1 at the beginning of the period

C_{A2j}: cost in the year j for the fossil based system A2 against which wood energy system A1 is compared

C_{A20}: denotes cost of the system A2 at the beginning of the year

C_{pg}: mean specific heat of the flue gas, kJ/kg °C

CB: kg of carbon burned per kg of as-fired fuel

CO: carbon monoxide

CO_2: carbon dioxide gas or percent of carbon dioxide in flue gas

d: discount rate

DFB: depth of fuel bed
EP: present value of fuel energy cost

DPB: discounted payback period

FFR: fuel feed rate, kg/h

h1: enthalpy of feedwater at boiler inlet, kJ/kg

h2: enthalpy of feedwater at boiler outlet, kJ/kg

ha: land area in hectare

h: time in hour

h_{fref}: enthalpy of the saturated vapor at reference temperature, kJ/kg

h_{gG}: enthalpy of the superheated water vapor at flue gas temperature, kJ/kg

h_{gref}: enthalpy of the liquid at reference temperature, kJ/kg

H: elemental hydrogen or weight fraction or percentage of hydrogen in fuel from fuel ultimate analysis

H_2: hydrogen gas or percent of hydrogen in air or in flue gas

HHV: higher heating value of fuel, kJ/kg

HO_2: water

GJ: Gega joules (10^9 joules)

i: interest rate

IP: present value of investment

IRR: internal rate of return

j: time period in years (j = 0, 1, 2, 3...n)

LDG: heat loss due to heat in dry flue gas, kJ/kg as-fired fuel

LFD: heat loss due to dust in fuel

LMA: heat loss due to moisture in combustion air, kJ/kg as-fired fuel

LMF: heat loss due to moisture in fuel, kJ/kg as-fired fuel

LMH: heat loss due to moisture from burning hydrogen, kJ/kg as-fired fuel

LRU: heat loss due to radiation and other losses unaccounted for

LUC: heat loss due to unburned carbon, kJ/kg as-fired fuel

LCC: Life cycle costs

kg: Kilogram

kJ: kilo joules (1000 joules)

m: meter

m.c.: moisture content

mm: millimeter

M: moisture in fuel (kg/kg of as-fired fuel)

MJ: Mega joules (10^6 joules)

MP: present value of operation and maintenance

M_w: water flow rate, kg/h

n: life period in years

N: elemental nitrogen or weight fraction or percent nitrogen in fuel, from fuel ultimate analysis

N_2: nitrogen gas or percent of nitrogen gas in air or in flue gas

NB: net benefits

NS: net savings

O: elemental oxygen or weight fraction or percent oxygen in fuel from fuel ultimate analysis

O_2: oxygen gas or percent of oxygen gas in air or in flue gas

PAD: primary air damper opening in millimeters

PB: payback period, years

Q_{in}: heat energy input from fuel, kJ/h

Q_{out}: heat energy added or delivered, kJ/h

RP: present value of replacement costs

S: elemental sulfur or weight fraction or percentage of sulfur in fuel from fuel ultimate analysis

SO_2: sulfur dioxide gas or percent sulfur dioxide in flue gas

S_n: salvage value at the end of n years

SP: present value of salvage

SAD: secondary air damper opening in millimeters

SIR: saving to investment ratio

SPB: simple payback period

RP: present value of replacement costs

T: temperature, degree C

TP: present value of taxes, insurance, shelter, etc.

T_{fg}: temperature of flue gas in degree C

T_{ref}: reference room air temperature in degree C

UF: unburned carbon kg per kg of as-fired fuel

W_{md}: water vapor in kg per kg of dry air

WAA: amount of actual air in kg per kg of as-fired fuel

WDA: amount of dry air in kg per kg of as-fired fuel

WTA: amount of theoretical air in kg per kg of as-fired fuel

INTRODUCTION

Energy plays a fundamental role in economic development and operation of our technological society. An adequate supply of energy in some form or other is used in attaining basic essentials of human life (food, water, and shelter) and improving the quality of life. The history of civilization is largely a story of man's progress in harnessing energy, the ability to accomplish work, by converting it into a useful form. There are three distinct types of energy sources: fossil fuels, fissionable nuclear fuels and non-fossil, non-nuclear renewable fuels. Many of the worlds's present problems generated by a rapid depletion of finite fossil energy resources and degradation of the environment from both fossil and fissionable nuclear fuels have revived interest in research and development in alternate and renewable energy resources.

The renewable energy resources can be divided into three groups: non-solar such as geothermal and tides; indirect solar such as winds and ocean thermal gradients and direct solar including photosynthesis. It is important to recognize that fossil fuels are renewed only on a geological time scale - million of years, whereas wood-biomass is renewed within years, grain and crop-biomass is renewed within months, and wind and sun energy are instantly available for harvesting with wind turbines and solar cells and collectors.

Among renewable energy resources, biomass materials or biofuels for energy production are widely recognized as a past, present and future reliable energy resource for humans (Office of Technology Assessment, 1980). The energy content of biomass fuel is derived directly from solar energy through the process of photosynthesis (Hall, 1978).

All fossil fuels such as coal, natural gas and petroleum originated from biomass materials and have been subjected to geological processes over the span of time. The geological processes formed physically and chemically different kind of fossil fuels as compared to fresh biomass materials. These processes increased thermal energy content per unit weight, virtually eliminated the moisture, increased material density and converted the biomass materials to fluid, as in the case of oil and gas or a readily handled solid, as in the case of coal (White and Plaskett, 1981).

Among biofuels, wood energy resources are receiving increased emphasis and are considered to be dominant renewable biofuels for energy production (Tillman, 1985).

Four primary considerations in developing wood-biomass energy system are: (1) availability of biomass energy resources, (2) optimum size, and design of energy system equipment, (3) optimum operating characteristics of the wood-fired energy system, and (4) economics of the production and use of wood energy when compared with fossil based systems. These four concerns were considered and analyzed in the development and operation of the McNay integrated wood-biomass heating energy system, at the Iowa State University McNay Memorial Research Center, Lucas County, in southern Iowa.

Wood Energy Perspectives

Wood, of course, is not a new fuel. Until about 1850, the U.S. relied on energy from wood-biomass for 90% of its energy needs (Office of Technology Assessment, 1980). Worldwide, even today about half the wood harvest is used directly for fuel. Bogach (1985) reported that the world consumption of fuel wood was about 15.92 billion GJ during 1980 (Table 1). The U.S. energy use pattern, Fig. 1, illustrates that the transition from fuel wood occurred in the 1880s when the U.S. shifted from wood resources to coal. In 1940s natural gas and petroleum became the predominant fuel. By 1970, the U.S. wood fuel consumption was down to 1 percent of the U.S. energy use. Since the energy crisis of 1973, wood energy has accounted for an increasing share of the total U.S. energy consumption.

The U.S. Energy Information Administration (1982) reported the results of a residential energy consumption survey of 1980 showed that wood was the fourth most commonly used primary heating fuel,

Table 1. Contribution of wood fuel in world energy consumption during 1980

	Population (millions)	Fuelwood[a] (million m^3)	Energy equivalent of fuelwood[b] (million of GJ)	Fuelwood (as % of total energy)[c]
World	4,372	1,631	15,921	6
Developed	1,173	149	1,454	1
Developing	3,199	1,482	14,467	24
Africa	435	369	3,603	58
Asia	2,399	825	8,054	20
Latin America	365	288	2,810	19

[a]Includes wood for charcoal.
[b]Energy content of wood is used 9.76 GJ per cubic meter.
[c]Total does not include crop biomass, residue, etc.

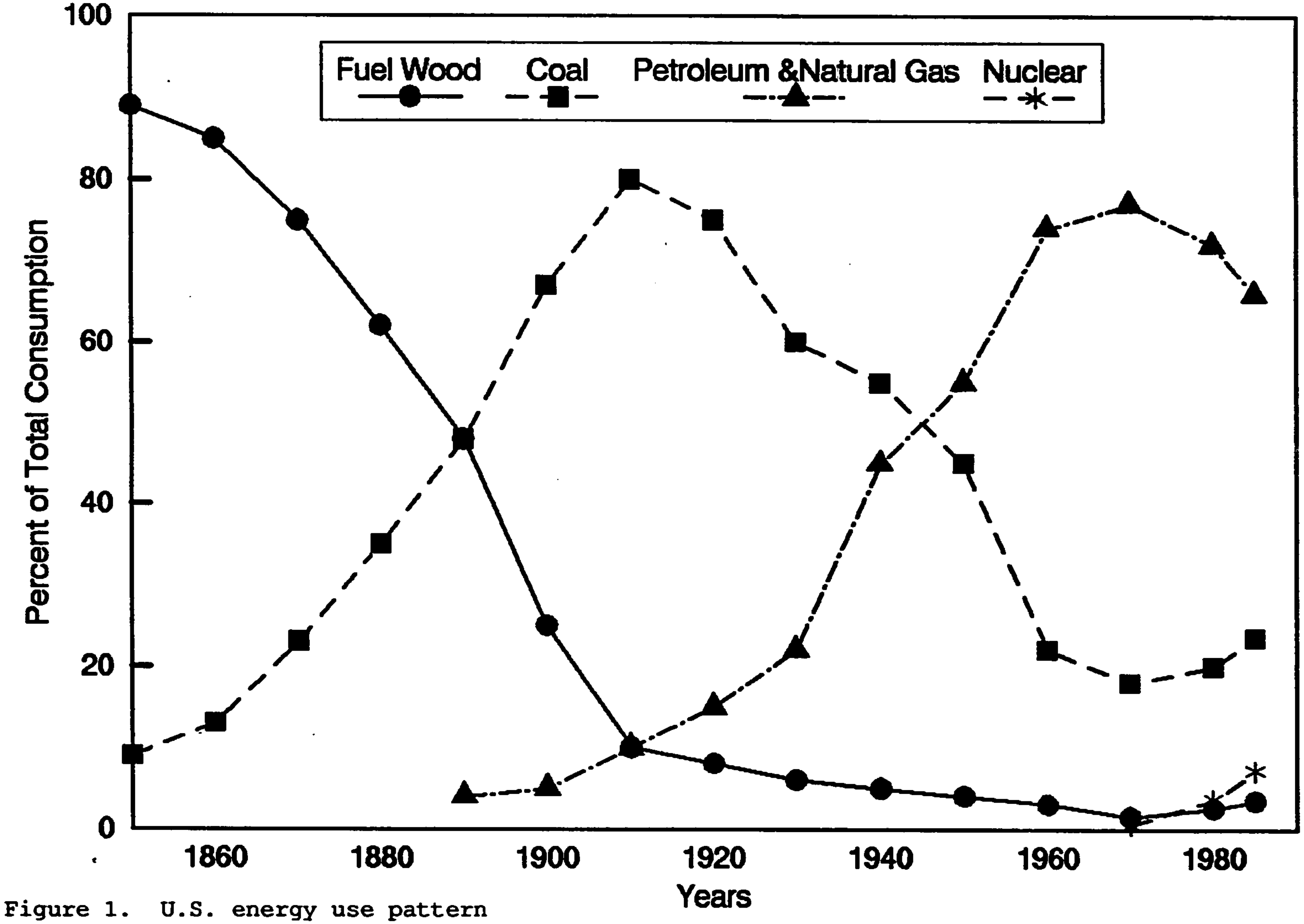


Figure 1. U.S. energy use pattern

replacing liquid petroleum gas. When primary heating use and secondary heating uses were combined, wood was the third most-used fuel, exceeding the number of users of fuel oil and kerosene. Natural gas was the dominant fuel, whereas electricity was the second-most-used main heating fuel in the residential sector of the United States.

The U.S. Energy Information Administration (1987) estimated that about 2778 million GJ of wood energy was produced in 1984. Almost 1771 million GJ of the wood energy was consumed by the industrial sector. In the residential sector wood supplied about 974 million GJ and 6.4 million households used wood as a main heating fuel. The consumption of wood-biomass increased about 47% between 1973 and 1984, and by 68% between 1971 and 1984. It is evident that increased consumption of wood fuels in the U.S. during 1984 resulted in the substantial displacement of conventional energy sources, particularly oil. The potential oil displacement resulting from the heat energy delivered by wood fuels in 1984 in the U.S. was about 452 million barrels, or equivalent to about 66 days of U.S. imported crude oil and refined petroleum products.

Schwieger (1980) reported that forests cover about 300 million ha of land area in the United States, and the vast amount of wood resource they contain is a viable fuel for domestic energy use. Sturos and Dickson (1980) focussed their discussion on possible future shortages of fiber, fuel, and food. They stated that because forests resources are renewable, they can reduce these potential shortages both in the short-and long-term if each tree resource is completely and efficiently utilized. Clark (1984) said the prospects for forest biomass use for energy in the United State are excellent. He emphasized that by proper managing and application of effective technology, forest wood can significantly contribute to fulfilling the total U.S. energy requirements. He suggested that the U.S. could substantially increase its wood energy use by developing better harvesting, handling and utilization techniques; by intensifying silviculture; and by wiser utilization of the resource by the end user.

Wood-Biomass Resources in Iowa

Iowa is rich in domestic energy resources; yet it imports 98% of its energy and exports about 5 billion dollars annually for energy to other states and countries. Iowa is at an agricultural and three "E's" crossroads (Energy, Economics and Environment). It can potentially achieve self sustaining and more diversified agriculture by adapting renewable biofuel resources for energy production. The Iowa Department of Natural Resources (1990), also highlighted the importance of the three 'E's for the State of Iowa. There are a number of long range and immediate specific benefits that can only be realized by using biomass resources for energy production:

1. Access to a continuous fuel supply, since biomass fuels are renewable within months or years, and are locally produced.
2. Substitution of heating energy use from fossil fuels to locally produced energy crops and forest wood resources could greatly reduce dollar export from Iowa for fuel purchases.
3. Biomass production and use of ash as an agricultural fertilizer will conserve land and water resources and reduce erosion and pollution problems.
4. Money saved from fuel purchase could be spent for creating new jobs and income opportunities for a better quality of life.
5. The environment would be cleaner.

Buchele and Marley (1978) discussed the importance and creative use of crop residues as an energy source for farmstead application, as well as the development of on-farm biomass energy systems in Iowa. Iowa Natural Heritage Foundation (1987), reported that the State of Iowa produces about 870 million metric tons of crop - biomass (residue) annually, having energy value of 875 billion MJ. Besides forest wood energy resources, only crop-biomass has the potential to generate energy that can fulfill 90% of Iowa's total energy consumption of 976 billion MJ. The forest wood resources account for about 4% (600 thousand ha) of the total land area in Iowa (Ostrom, 1974). Spenser and Jakes (1980), reported that 85% of Iowa's total commercial forest land of 584 thousand ha is concentrated in the eastern half of the state - the southeastern (45%) and northeastern (40%). The western survey unit in Iowa, with state land area of 43% contains only 15% of the total commercial forest area. Most woodland areas in Iowa are generally under utilized and poorly managed (Honeyman et al., 1988). The forest resources are located along streams and consists of land not readily accessible or suited for traditional agriculture, but well located for energy production. Countryman et al. (1985) prescribed improved management practices for increased production of forest wood resources in Iowa. They estimated that more than 50% of the standing volume of three upland timber types in eastern Iowa is available for harvest under silvicultural practices appropriate for domestic energy production.

Farmers own two-thirds of the total woodland resources in Iowa, and about 62% of the farmers with woodlands own tracts of woodland of 20 ha and larger. These are large enough to provide energy for on-farm use. Spenser and Jakes (1980), also reported that saw timber stands of white oak-red oak-hickory and elm-ash-cottonwood frequently occur on farmer owned land. Honeyman et al. (1988) reported that the Conservation Reserve Program (CRP) in Iowa has placed a great emphasis on controlling soil erosion problems by utilizing potentially erodible lands for energy plantation. These can provide wood-biomass for heating, or can contribute towards reforesting natural woodland areas. The Iowa Energy Policy Council (1985) reported that the State of Iowa has a potential for developing wood as a viable alternate crop and energy source.

McNay Integrated Wood Energy System

Iowa State University has undertaken a project to research and demonstrate the use of wood-biomass as an alternate heating energy source for farmers and small industries at its McNay Research Center in southern Iowa. The purpose of this project is to demonstrate and provide research results to Iowa farmers from several concepts of an integrated on-farm wood-biomass heating energy system and the management of domestic energy resources, for potential substitution for imported heating fuels. These include: (1) on-farm forest wood resource management and harvest (2) wood-biomass burning and heating system for the farmstead (3) energy plantation as a viable alternate farm crop and energy resource.

The McNay Research Center is Iowa State University's active presence in southern Iowa, a distinct area with unique challenges and opportunities in scientific agriculture. The McNay Center is comprised of about 800 ha, of which 64 ha are existing woodland area and 22 ha are being planted as an energy plantation. The existing woodland area and McNay farmstead are typical of many southern Iowa farms. The farm residence and shop have a large heating fuel energy consumption of 441,000 MJ's annually (Honeyman et al., 1988).

The project consists of an integrated wood-fired hot water boiler system for heating a farm residence, farm shop and offices, and for grain drying. The system consists of all equipment necessary to harvest, chip, store, deliver and burn the wood.

OBJECTIVES

The major objectives of this research were to determine the performance of the wood-fired boiler energy system and to determine the basic principles of operation of an integrated wood chip fired hot water boiler system for space heating for farmstead applications. The specific research objectives include:

1. To measure and evaluate the effect of various boiler design parameters on thermal and emission performance of the wood-fired boiler energy system.
2. To determine and monitor the seasonal energy quantity delivered to the farmstead heating system by developing an energy measuring instrumentation and data logging system.
3. To investigate factors related to convenience of operation, wood fuel and ash handling, trouble shooting and safety.
4. To analyze operating data of an integrated system to determine the energy and economic cost of wood energy, using net energy analysis and life-cycle cost analysis, and to make comparison with fossil based systems.

LITERATURE REVIEW

Characteristics of Wood Fuel

Wood fuels have physical and chemical characteristics that are important to the design and operation of wood energy systems. The characteristics of wood fuels vary by tree species, age of the tree and wood materials (i.e., bark, stem-wood or branch-wood).

Physical characteristics

Physical characteristics of wood-biomass fuels include specific gravity, bulk density and moisture content. Specific gravities and bulk densities are important because they strongly affect storage and material handling system requirements. Specific gravities and bulk densities for biomass fuels range from 0.2 - 0.45 and 200 - 450 kg/m^3 for most wood species (Tillman, 1985). These values are low compared to coal, which has a specific gravity range from 1.2 -1.4, and bulk density from 1200 - 1400 kg/m^3.

Moisture content is an especially significant issue because it directly affects the net heating value of the wood fuel, its ignition properties, and the efficiency of wood fuel utilization. Wood is hydroscopic and absorbs and adsorbs water (Tillman, 1978 and Cheremisinoff, 1980). Moisture content of wood can be expressed as percentage moisture content oven dry basis or as-received. Typical moisture values for as-received hogged wood and bark range from 38 to 55% for hogged wood and bark.

The heat energy that can be released by burning biomass fuel is the heating value of that fuel. The heating value of wood fuels can be expressed as higher heating value (HHV) or lower heating value (LHV). The lower heating value is also called net heating value (NHV). The higher heating value represents the heat of combustion when any water formed during combustion is condensed to a liquid. The higher heating value (HHV) is experimentally determined by using an adiabatic bomb calorimeter which measures the enthalpy change between reactants and products at 25°C. The lower heating value (LHV) is based on the water in the combustion products remaining in the gaseous form. The difference between HHV and LHV is the latent heat of the water in the combustion products.

Harris (1984) determined heating values for stems and branches in three hardwood species: white oak, yellow poplar, and sweetgum. He found a significant difference between higher heating values of the stem-wood and branch-wood of white oak. No difference was detected between stem-bark and branch-bark for any of the three species tested. Annamalai et al. (1987) compared the estimated and measured heating values of biomass fuels. They concluded that the higher heating values (HHV) of biomass fuels can be estimated with maximum error of 5%, knowing ultimate or elemental analysis (C, H, O, N, S analysis) of biomass fuel, by using the following equation:

$$\text{HHV, kJ/kg} = 35{,}160\ C + 116{,}225\ H - 11{,}090\ O + 6280\ N + 10465\ S \qquad (1)$$

Where C, H, O, N, S are decimal fraction of carbon, hydrogen, oxygen, nitrogen and sulfur in the wood.

The heating value of wood fuel can be reported on both wet and dry fuel basis. The conversion between moisture basis is simpler for HHV than for LHV. For HHV moisture present in the wood fuel is in the same state (liquid) before and after combustion. The influence of moisture on higher heating value can be calculated by the following formula:

$$HHV_1 = HHV_o\ (1 - M) \qquad (2)$$

where

HHV_1 = actual higher heating value of wood fuel, MJ/kg

HHV_o = oven dry higher heating value of wood fuel,MJ/kg

M = moisture content, decimal (as-received basis)

Lower heating value depends on the moisture content in a more complicated fashion (Reed, 1981). Since both the product water and moisture are present as vapor after combustion, a portion of the heat of combustion is used to evaporate the moisture. Harris et al. (1986) developed a relationship to compute lower or net heating value for wood fuel by making a correction for the latent heat of vaporization of the water generated during combustion (due to presence of hydrogen in the fuel) and latent heat of vaporization of water carried with the fuel.

$$LHV \text{ or } NHV = HHV_o - (LH + HHV_o) M \qquad (3)$$

where

LH = latent heat of vaporization of water at the referenced temperature of 25°C, 2437 kJ/kg.

Table 2 presents the higher heating values (HHV) of some biomass materials and fossil fuels on as-received basis and dry basis.

Chemical characteristics

The chemical characteristics of wood important for energy generation are chemical structure, heating value, and ultimate and proximate analysis. Wood is composed of a variety of substances. The main constituents are cellulose ($C_6H_{10}O_5$), lignin ($C_9H_{10}O_3(OCH_3)_{0.9-1.7}$), and hemicellulose (such as xylene $C_5H_8O_4$), and extractives and various ash-forming minerals.

Trees are generally categorized as hardwoods or softwoods. Hardwoods contain about 40 - 50% cellulose, 16 - 25% lignin and 22 - 40% hemicellulose (on an extractive free basis), while softwoods contain 40 - 45% cellulose, 24 - 37% lignin, and 25 - 30% hemicellulose (Tillman, 1978 and Tillman et al., 1981).

Table 2. Higher heating value (HHV) of some biomass and fossil fuels

Fuel type	Moisture content %	Higher heating value MJ/kg	BTU/lb
Corn cobs	35	12.4	5,336
Corn stover	35	11.8	5,073
Soybean straw	15	13.4	5,764
Small grain straw	15	13.2	5,667
Whole tree chips	45	11.2	4,800
Mill (wood) residue	13	16.3	7,000
Densified wood fuel	8	18.6	8,000
Average values on oven dry basis			
Agricultural residue		17.4	7,500
Wood		20.0	8,600
Coal		27.9-31.4	12,000-13,500
Oil		41.9-46.3	18,000-19,900
Natural gas		43.1	18,550

The extractives range from 5 - 30% among wood species. The extractives in wood are important to various wood properties, such as color, odor, taste, decay resistance, strength, density, and flammability (Cheremisinoff, 1980). Minor ash-forming minerals, such as silica, phosphate, potassium, and calcium, generally comprise from 0.1 - 3% of wood. Tillman et al. (1981) found that wood with high extractive contents have a higher energy content than those of lower extractive contents.

The proximate analysis determines the percentage of volatile matter, fixed carbon and ash content in a fuel. The ultimate analysis determines percentage of individual elements such as carbon, hydrogen, oxygen, sulfur, nitrogen and ash. Babcock and Wilcox (1978), Tillman et al. (1981), Schwieger (1980) and Stout (1984) have discussed proximate and ultimate analyses for a variety of fuels along with higher heating values of those fuels. Table 3 indicates proximate and ultimate analyses and higher heating values (HHV) for selected fuels. Typical dry softwoods have a higher heating value in the range of 20.9 - 23.2 MJ/kg, whereas dry hardwoods have a higher heating value of 18.6 - 20.9 MJ/kg.

Table 3 also illustrates that biomass fuel are highly volatile and oxygenated and have moderate heating value as compared to coal. The reactivity of fuels can be measured using hydrogen/carbon (H/C) and oxygen/carbon molar ratio, and the volatile/fixed carbon ratio.

Table 4 shows these measures of reactivity for all fuels presented in Table 3.

The comparison of elemental analysis of wood with coal also demonstrates that wood fuel contains little sulfur, nitrogen and ash-forming constituents. This indicates that clean wood is relatively clean burning and environmentally sound.

Combustion Mechanism of Wood Fuel

Wood combustion process

There are two major conversion processes of biomass materials; namely thermal and biological, which convert biomass materials into useful energy via heating and microbiological action (Hiler and Stout, 1985). The thermal conversion processes consist of direct combustion, gasification and pyrolysis. Direct combustion is a complete oxidation process where liberation of heat is the major objective. Gasification is a partial oxidation process that results primarily in combustible gases. Pyrolysis is a non-oxidative thermal process that results in gases, liquid and char.

The major application of wood fuel energy is the production of heat by direct combustion for space heating and crop drying, or to produce steam for electricity generation. Combustion may be defined as the rapid chemical combination of oxygen with the combustible elements of a fuel (Babcock and Wilcox, 1978). The primary chemical

Table 3. Proximate and ultimate analysis of some selected fuels[a]

Analysis	Douglas -fir	Western hemlock	Pine bark	Bagasse	Rice hulls	Cotton gin trash	Coal[b]
Proximate[c]							
Volatiles	85.8	83.8	72.9	83.8	64.5	81.1	33.9
Fixed carbon	13.4	14.0	24.2	12.7	12.9	8.9	55.8
Ash	0.8	2.2	2.9	3.5	22.6	10.0	10.3
Ultimate[c]							
Hydrogen	6.3	5.8	5.6	5.8	4.4	5.2	5.0
Carbon	52.3	50.4	53.4	48.8	38.3	43.2	75.5
Oxygen	40.5	41.4	37.9	41.7	33.9	40.1	4.9
Nitrogen	0.1	0.1	0.1	0.2	0.8	1.5	1.2
Sulfur	-	0.1	0.1	-	-	-	3.1
Ash	0.8	2.2	2.9	3.5	22.6	10.0	10.3
Higher heating Value							
MJ/kg	21.05	20.05	21.0	19.37	13.81	16.51	31.74

Table 4. Measure of reactivity for some selected fuels

Fuel	H/C ratio (molar)	O/C ratio (molar)	Volatile/Fixed carbon ratio
Douglas-fir	1.44	0.58	6.40
Western hemlock	1.38	0.62	5.99
Pine bark	1.26	0.53	3.01
Bagasse	1.43	0.64	6.60
Rice hull	1.38	0.67	5.00
Cotton gin trash	1.44	0.70	9.11
Bituminous Coal	0.79	0.05	0.61

products formed during wood fuel combustion are carbon dioxide and water. These reaction are exothermic, and the heat released is approximately 32.73 MJ/kg (14,100 BTU/lb) of carbon burned and 141.81 MJ/kg (61,100 BTU/lb) of hydrogen burned. The basic chemical reaction for hydrogen and carbon can be illustrated by the following equations:

$$C + O_2 \text{ ---------> } CO_2 + 32.73 \text{ MJ/kg C} \tag{4}$$

$$2H_2 + O_2 \text{ ---------> } 2H_2O + 141.81 \text{ MJ/kg H} \tag{5}$$

The oxygen required to complete the chemical reactions comes from both the fuel and the atmosphere.

The objective of good combustion is to release all heat from the fuel while minimizing losses from imperfect mixing and excess air. The combination of the combustible elements and compounds of a fuel with oxygen requires:

1. temperature high enough to ignite the fuel constituents in oxygen or air.
2. mixing or turbulence of the air stream
3. and sufficient reaction time for complete combustion process.

These factors are commonly referred to as the "three T's" of combustion:

1. Temperature

2. Turbulence

3. Time

Arola (1978), Schwieger (1980) and Stout (1984) divided actual combustion of wood into three phases:

1. the evaporation of moisture from the fuel

2. the distillation and the burning of the volatiles

3. and the combustion of the fixed carbon.

Once the fuel wood is injected into the combustion chamber, the moisture immediately starts to be driven off. After moisture has been evaporated, heat is absorbed by the fuel, raising the temperature and driving off the volatile gases. Hence, these gases are burned to sustain the combustion. When most of the volatile are distilled out of the wood, the highly reactive surface of the remaining fixed carbon is burned in the presence of oxygen.

Shafizadeh (1982) explained that the process of wood combustion involves a complex series of physical transformations and chemical reactions which are further complicated by the heterogeneity of the wood fuel. Edward (1974) presented a conceptual model of solid fuel combustion (Fig. 2). In this combustion model, five reaction zones can be identified:

1. Heating and drying

2. Solid particle pyrolysis

3. Precombustion gas-phase pyrolysis

4. Gas-phase oxidation

5. Char oxidation

Heating and drying occur in the non-reacting solid zone. Both solid particle pyrolysis and char oxidation occur in the condensed phase reaction zone. Tillman et al (1981), and Tillman (1981, 1985) adopted this model of solid fuel combustion for wood fuels and described the pathways and mechanism associated with wood fuel combustion.

Oren et al. (1987) studied the mechanism of dry wood combustion through a quantitative monitoring of stack flue gas. They determined that the combustion of wood occurs in three stages. The first stage is an accelerated burning during which the chemical composition of the burning fraction is virtually constant, approximately that of the initial dry wood and is independent of air flow rate. The second stage involves a rapid change in hydrogen/carbon ratio. The third is the combustion of charcoal. During this stage the chemical composition of the combusting fraction is once again effectively constant and is independent of air flow rate.

Zayed et al. (1987) further studied the mechanism of dry wood combustion by measuring the weight loss at 750 degree C. They reported that the rate of weight loss increased for an initial period of about 60 seconds; thereafter it decreased asymptotically in an overall first order reaction.

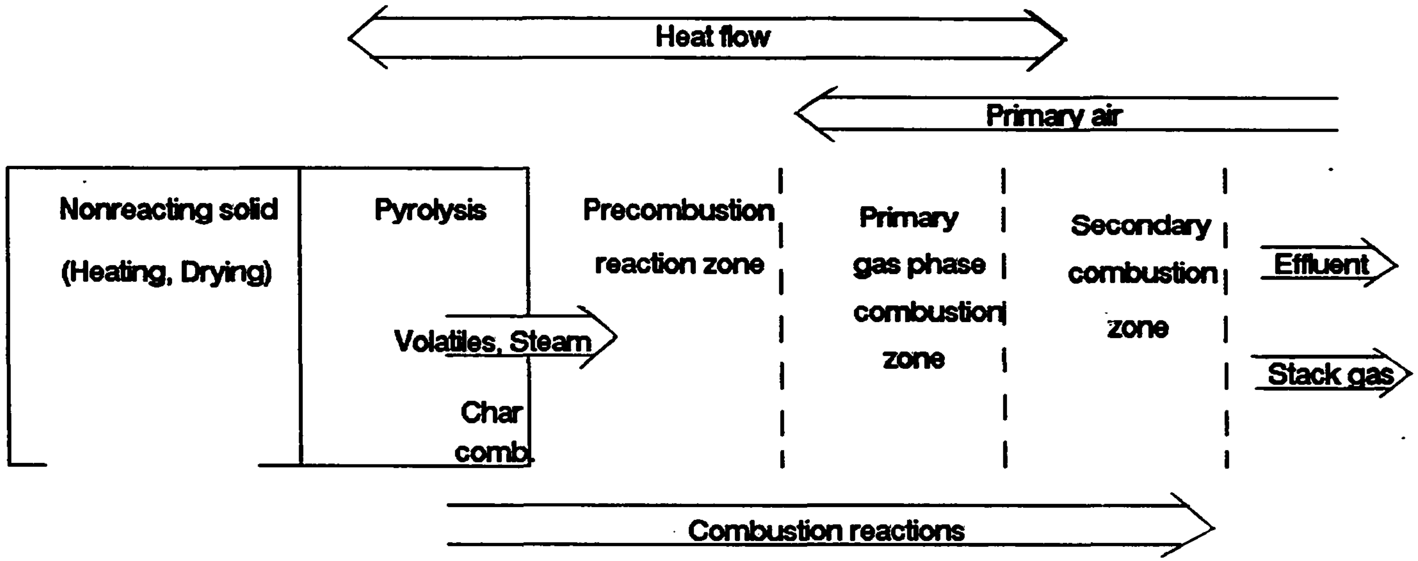


Figure 2. The conceptual model of solid-fuel combustion, after Edwards (1974)

Wood combustion systems

The production of hot gas or hot water or generation of steam are the most common uses of wood-fired boiler thermal energy systems. The boiler technology for wood is established through long use in the pulp and paper and other related industries (Topely, 1984). The wood fuel gives off heat when burned in the combustion system. The air support the combustion of the wood fuel. The products of combustion are hot flue gases which carry the heat through the boiler and give up heat to a working fluid through the heat transfer surface.

A boiler is an enclosed vessel of water heated by the gases from the combustion process. In a steam boiler system the output of useful heat is carried by the steam, and in a hot water boiler the useful heat is carried in a stream of hot water. Two general configurations of wood-fired boilers are used: the firetube boiler, in which the gases travel through the tubes passing through a water jacket in the boiler, and water tube boiler, in which the water being heated passes through tubes that are themselves heated on the outside by the hot gases (Babcock and Wilcox, 1978)

In any wood energy application, the combustion system is designed to make the best use of "three T's" of combustion (Temperature, Turbulence, and Time). The production of useful heat is influenced not only by the fuel conditions and the process of wood combustion, but also by the design of the wood combustion system (Tillman et al., 1981). Combustion systems are generally classified by the way they burn wood fuel, and are listed below:

1. Pile burning
2. Spreader stokers
3. Suspension burning
4. Fluidized bed burning

All these combustion systems are applicable for space heating, drying or steam generation. These combustion systems have been extensively discussed by Schwieger (1980), Levi and O'Grady (1980), Cheremisinoff (1980), and Great Lakes Regional Biomass Program (1987). These prominent wood-fired systems are briefly reviewed below.

Pile burning system

Pile burning systems are selected where a high moisture fuel must be burned. These are relatively simple, quiet burning systems. The traditional Dutch oven, the Wellons fuel cells, and inclined grate are all examples of pile burning system (Tillman, 1981).

The Dutch oven design consists of a two-stage furnace, in which moisture is evaporated and the fuel is gasified. A secondary furnace is used to complete the combustion process. Wood fuel is gravity fed through the top of the Dutch oven. Fig. 3 illustrates a steam boiler with a Dutch-oven furnace. It is reported that dutch-oven furnaces were utilized almost exclusively until the late 1940s.

The inclined grate pile burning system has the advantage of size flexibility. In an inclined grate pile burning system the fuel is fed to the top of the grate, where heating and drying occur. As the fuel slides down the grate, solid-phase pyrolysis occurs. The volatiles evolved enter a secondary combustion chamber (Fig. 4). The char moves further down the grate, where char oxidation takes place. Finally, ash is removed from the lower part of the grate. Control of primary air for char oxidation and secondary air for volatile oxidation ensure the separate combustion zones - precombustion reactions and postcombustion gas phase reactions (Tillman et al., 1981).

Pile burning system have large areas of refractory that are exposed to the hot combustion gases and permit the burning of wood fuels with a moisture content as high as 55%. The narrow chambers of pile burners effectively increase turbulence and mixing of air and fuel. Great Lakes Regional Biomass Program (1987) reported that these units have slow response to demand fluctuations and have high refractory maintenance.

Spreader-stoker systems

Like pile burning, spreader-stoker systems involves grate firing, and the grate design may be inclined, moving, or stationary. The

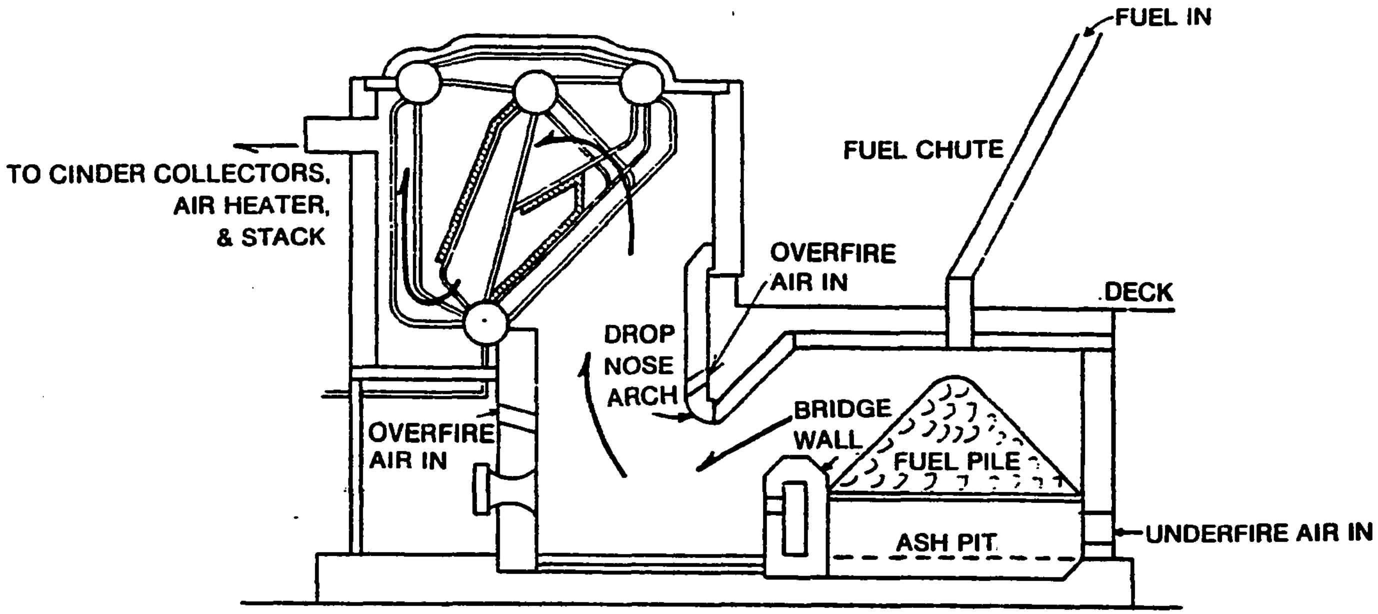


Figure 3. Pile burning system - Dutch oven, after Levi and O'Grady (1980)

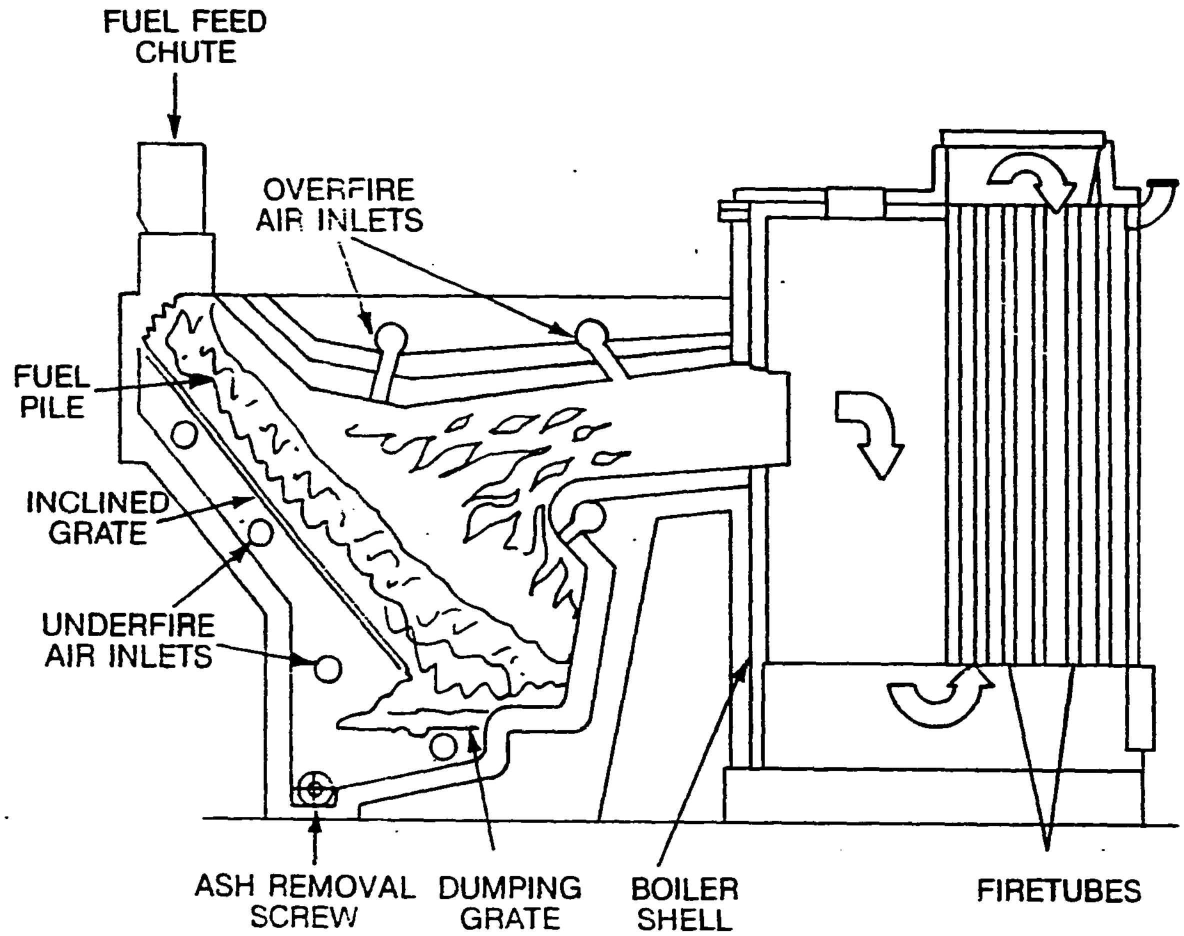


Figure 4. Pile burning system - inclined grates, after Tillman et al. (1981)

grates are made of either cast iron, or refractory bricks. In the spreader-stoker, wood fuel is introduced (spread) above the grate into the furnace either by a pneumatic or mechanical spreader (Junge, 1979). A portion of the fuel undergoes combustion while in suspension and the remainder falls to a series of grates where combustion is completed (Fig. 5). Solid phase pyrolysis and char oxidation occur on the grates: Gas phase oxidation occurs either throughout the furnace, if most air enters as primary air, or in the vicinity of the zone where secondary air is introduced if the undergrate air is limited to sub-stoichiometric quantities (Tillman et al. 1981).

Primary air flowing through the grates (underfire air) serves several purposes (Levi and O'Grady, 1980): (1) it provides oxygen for combustion of fixed carbon, (2) it cools the grate, (3) it promotes turbulence in the fuel bed, and (4) it contributes to drying the fuel.

Secondary air is also introduced above the grates (overfire air) to promote turbulence and to complete the combustion of entrained and volatilized material. Careful and proper control of combustion air is important in spreader-stoker wood-fired furnaces.

It is reported that newer steam plants fueled by wood and bark utilize this design because it can be used to feed a wide range of fuel types. The spreader-stoker is relatively insensitive to load

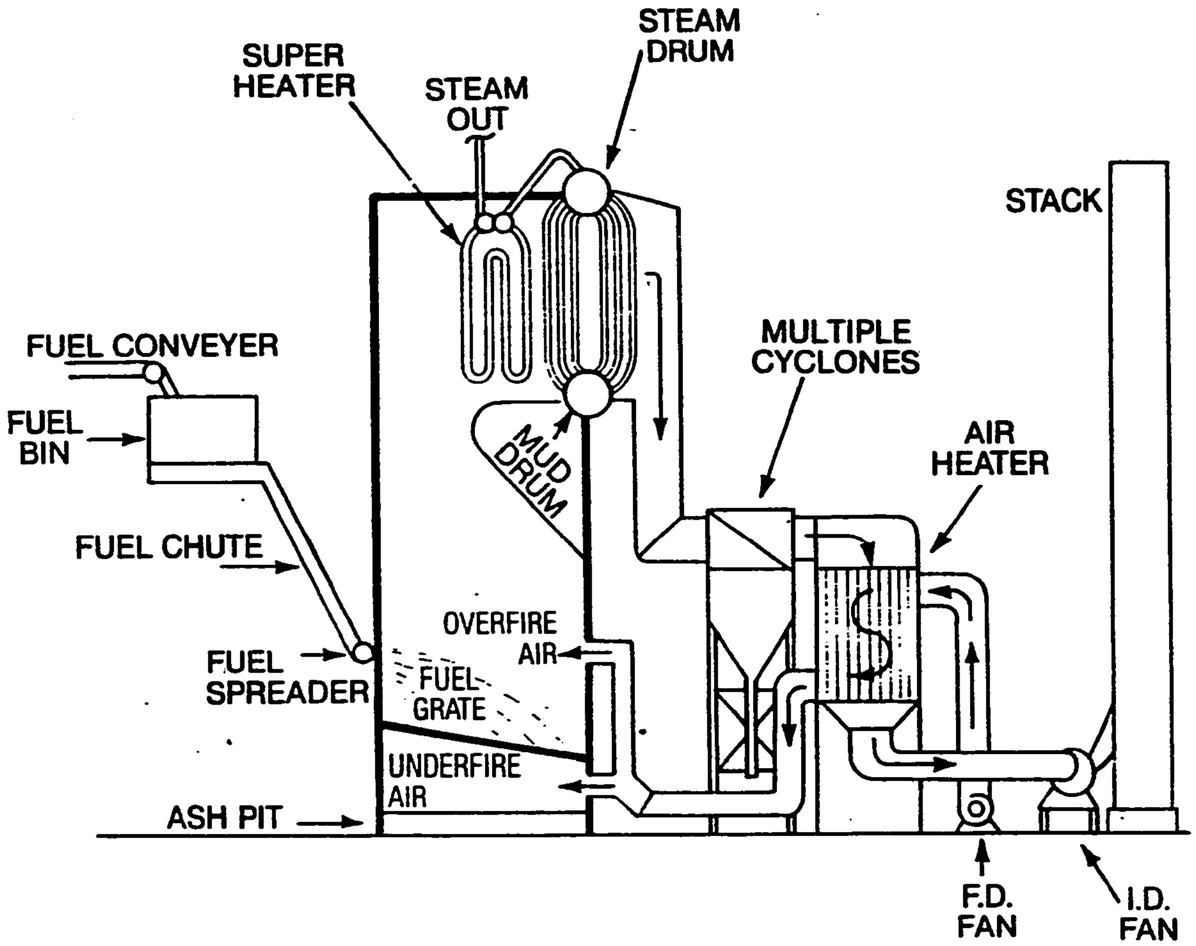


Figure 5. Spreader stoker with grate burning system, after Junge (1979)

fluctuations since ignition is almost instantaneous on increase of firing rate, and the fuel on the grate will burn out rapidly when the load is reduced.

Suspension burning system

In suspension burning systems, combustion occurs while the finally divided dry fuel particles (with moisture less than 15% and size less than 2 mm) are suspended in an air stream. All combustion reactions occur while the particle is in suspension Tillman et al., 1981).

It is reported that the combustion reactions in each particle occur sequentially; that is, heat-up occurs first, followed by pyrolysis, gas-phase reactions, and carbon oxidation. The thorough mixing of the air and fuel yields high net efficiencies and low excess combustion air. This system gives comparatively quick response to load fluctuations.

Fluidized-bed combustor system

A fluidized-bed combustor (Fig. 6) consists of a cylindrical, refractory-lined furnace with: (1) a perforated air distribution plate on the bottom, (2) a hot gas outlet at or near the top, and (3) ports for introducing fuel. The combustion air suspends a hot bed of inert material, such as sand, throughout the combustion chamber and provide the oxygen for combustion reactions. A pneumatically fluidized mass of sand serves the purpose of grates and to some extent serves the purpose of refractory walls of the combustion chamber. Initially, the unit is heated to a very high temperature with injection of fuel oil or natural gas. Once the proper bed temperature is reached, wood fuel is fed or injected into the bed; the wood burns in suspension and the fluidized bed very much resembles a boiling liquid because of its high turbulence. The primary functions of inert material used in a fluidized-bed are (Schwieger, 1980):

1. to disperse incoming fuel particles throughout the bed.
2. to heat the fuel particles quickly to ignition temperature.
3. to act as a flywheel for the combustion process, by storing a large amount of thermal energy.
4. to provide sufficient residence time for complete combustion.

Great Lakes Regional Biomass Program (1987) stated that the main advantage of fluidized-bed systems is that they may be retrofitted onto some oil and gas boilers that cannot accept other wood burners. These are capable of efficiently burning high moisture wood fuels such as green mill residues and wood chips.

For a fluidized bed to operate, the gas passing upward through the bed must be at some minimum velocity. The required velocity is a function of the size, shape and density of the bed medium. Gas

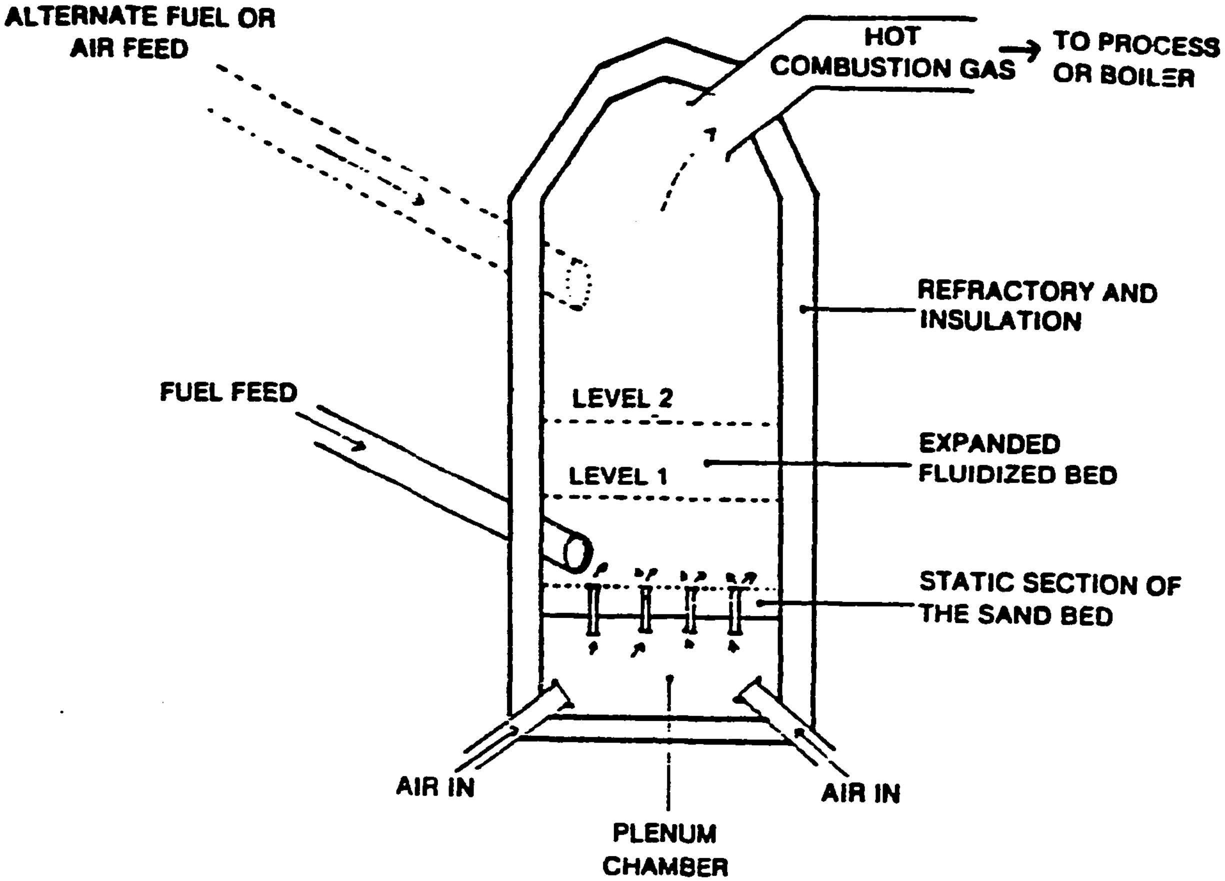


Figure 6. Fluidized bed burning system, after Great Lakes Regional Biomass Program (1987)

velocities in excess of the minimum value required for fluidization do not necessarily improve operation (Cheremisinoff, 1980). Excess gas velocities can cause localized spouting, excessive bed material carryover and a shorter time for proper combustion to take place, all of which reduce the efficiency of the fluidized-bed combustion system. The volume of excess air used in fluidized-bed combustion is typically 100-140%. It is absolutely essential to hold the combustion temperature below ash fusion temperature due to the large mass of inert bed material. This limits the efficiency of the system. The wood-fired fluidized-bed, however, generates high particulate loading in the flue gases caused by the carryover of bed material into the flue outlet.

Wood-Biomass Energy Systems

Investigations have been conducted at Iowa State University using direct combustion systems for converting agricultural crop residue to thermal energy. An incinerator-type furnace was developed by a senior design class for burning cornstalk to provide heat for drying high moisture grain (Kajewski et al., 1977). The test results indicated that crop residues are economical source of energy for grain drying. The design class suggested additional quality testing of the grain to evaluate the acceptability of biomass dried corn in the market.

Dairo (1979) developed and further tested the above cornstalk-fired furnace. He found a significant effect of feed rate on the flue gas temperature and efficiency of the furnace. He suggested additional work to improve the overall performance and effectiveness of the furnace for grain drying.

Claar et al. (1980) designed, developed, and tested a concentric-vortex, agricultural residue furnace. The furnace was designed to provide sufficient time, temperature, and turbulence of the combustion gases to permit complete combustion of fuel. The furnace was tested by burning a variety of agricultural crop residues. The furnace combustion efficiency was measured at various fuel feed rates and air flow rates. It was suggested that the vortex furnace could also be used for grain drying and heating hot water for farmstead applications.

Anderson et al. (1981) used a blend of ambient air and flue gases from the above furnace to dry high moisture corn by using corn cobs as fuel. Chemical analysis of the dried corn indicated no hazardous residues. Minor corrosion and discoloration were observed on the surface of the dryer blower from the products of combustion.

Wahby (1982) tested the vortex furnace for converting corn cobs into thermal energy. He also studied the corrosion rate of the furnace. The performance of the furnace was determined by varying corn cob feed rate and air damper opening and their effect on stack gas temperature, furnace efficiency and excess air. The highest efficiency obtained was 85% at a feed rate of 82 kg/h and air flow rate of 1810 kg/h.

Morey and Lang (1987) reported that a wood chip fired combustor was used to provide heat energy for grain drying in a bin drying system. A total of 828 metric tons (32,600 bushels) of corn were dried from 19.4% moisture to 14% moisture. The dryer consumed about 49 metric tons of green wood chips at 35% moisture (wet basis). The thermal energy output of the furnace averaged 897 MJ/h with an average system conversion efficiency of 56%.

Significant use of wood-biomass for residential space heating and other farmstead applications requires development and evaluation of improved operating systems that approach the operational ease of gas or oil fired systems.

Evans et al. (1981) investigated the combustion of wood in a single-stage burner. The gaseous products and particulate matter were monitored and analyzed. The results obtained confirmed that the amounts of pollutant products released are considerably less than from fossil fuels (coal, gas and oil) and that oxygen-rich conditions reduce the amount of carbon monoxide released. They concluded that wood can be considered a relatively clean fuel, apart from particulate material which it released.

Schneider (1984) measured combustion and efficiency of wood chip stoker heating systems over several heating seasons. He found a linear relationship between a chip stoker fired heating system's capacity factor and degree days; capacity factor increasing with the degree days. Capacity factor in turn is linearly related to system efficiency, with higher capacity factors giving higher efficiencies. The efficiency range for this relationship was found to be 30 to 50%.

Dadkah-Niko and Bushnell (1987) presented an analysis of wood combustion based on the first and second laws of thermodynamics. The effects of various parameters (such as wood fuel moisture contents, variation in particle size and different types of combustion system) on the wood combustion and efficiencies of the process were been studied. The results indicate that the most efficient conditions for wood combustion can be achieved by using the minimum amount of excess air at the highest permissible temperature. It can also be concluded that the lower wood fuel moisture contents result in higher combustion efficiencies.

Tuttle and Junge (1978) studied emission from combustion of wood residue fuel in an experimental spreader-stoker boiler. Particulate emissions were measured to determine the effects of under air flow rate and fuel bed depth on particulate carryover. A 4x2 factorial experiment without replication was designed to test the effects of fuel bed depth and energy release rate (kJ/h-m^2 of grate) on particulate emission. The independent variables were fuel feed rate and fuel bed depth; the dependent variable was the particulate emission rate from wood residue combustion. It was found that increased energy released increased particulate emissions. Increasing the fuel bed depth decreased the particulate emissions and the effect of the deeper bed is more pronounced at higher combustion rates. The most important results of this research were that a fuel bed several inches thick in a wood fired spreader-stoker can be used to meter the underfire air effectively to reduce particulate emissions and to increase the heating value of the gases produced in the fuel bed, which become fuel for the overfire combustion.

Adams (1979,1980) developed physical and chemical models of a burning wood-waste fuel bed for predicting the influence of fuel and operating parameters on particulate emissions. He reported that these models can be used to determine the mass and energy balances, influence of undergrate airflow rate, fuel feed rate, and fuel size distribution on particulate emission from a wood-waste boiler.

Spurrell et al. (1987) combined results from several wood fuel combustion studies in order to better understand the physical process of char carry-over and resultant loss of combustion efficiency in wood-fired spreader stoker furnaces. They found that for typical fuel size distributions, the fraction of fuel entrained can be as little as 10% but is typically greater than 50%. They also reported that under typical furnace conditions, the volatile fraction of the wood is approximately 90%, so that char will constitute only about 10 % of the original dry wood mass. Devolatilization is very rapid for the entrained particles, so the char combustion rate is the most important factor in determining carry-over.

Automatically controlled wood chip furnaces have been developed for commercial and institutional applications for space heating and for hot water at the University of Maine, Orono, Maine (Huff et al., 1976, Riley et al., 1979, and Smith et al.; 1980). In early 1973, a student research project was initiated at the university of Maine to investigate the possibilities for waste wood as a source of residential heat energy in New England. The first prototype furnace with a capacity of 52,750 kJ/h was developed and tested while burning dry wood chips. After getting promising results, a full scale project was initiated aimed, at designing, testing, modifying, improving and commercializing combustion equipment for burning wood fuels and associated supply, processing, storage and delivery systems (Riley and Smith, 1984). It was also reported that the wood chip furnaces developed at the university of Maine are gaining acceptance as commercially marketable equipment. Problems have been identified in the area of economics (relative capital and fuel costs), uncertainty of fuel availability, the psychological barriers of using an "unconventional" fuel, and health and safety concerns. By 1982 about 30 furnaces were operating, with accumulated operation of 100,000 hours. Efforts were also directed towards setting up an integrated system for processing, storage and delivery of wood chip fuels.

Short (1982) reported the results of a wood chip fuelled, stoker fired hot water boiler, which has been used over a period of three years as the sole source for both space and domestic hot water in a single family house. The performance of the wood system, while burning dry wood chips (21% moisture) was found to be comparable to that of original oil fired boiler. The wood-fired system saved 4300 liters of oil and consumed about 10 metric tons of wood chips annually. The wood-fired boiler thermal efficiency was determined to be about 30% when producing only hot water, and about 53% while supplying space heat as well. The system required refueling at least once a day during the heating season and thus requires greater attention for smooth running.

The Institute of Man and Resources in Canada carried out a demonstration program of ten wood fired residential central heating systems (Brandon, 1980). Four of the systems used chip wood fuel, one used pellet wood fuel, and two of the systems used water thermal storage (Brandon, 1981). This demonstration showed small combustion units to be able to use wood fuel cleanly, efficiently and with excellent homeowner convenience. The project recommended more work to determine the relationship between efficiency testing on an input-output basis and using a stack loss method.

Dixit and Brown (1982) reported that a small wood-fueled steam boiler capable of producing 6000 kg/h of saturated steam was installed in a textile mill located in Aragon, Georgia. The overall performance of the wood energy system was studied for six months with respect to its operational aspects, emission and economics. It was observed during the start-up period that wood fuel with moisture content in excess of 55% would cause problems in sustaining combustion. Instantaneous boiler efficiency of about 60% was determined using "heat loss method". Data were also collected about particulate emissions. The analysis indicated that particulate emissions from a small wood-fired steam boiler facility were not a problem and found the boiler to comply with all applicable emission standards.

Brown et al. (1985) presented the analysis of 3 years of operation of the above wood-fired boiler system. The analysis showed that the wood system responded adequately to variations in steam demand and to fuel of various qualities. The system was considered to be reliable and simple to operate. The economic analysis demonstrated that the boiler achieved the projected levels of savings and yielded a favorable economic payback period of 3 years. The system operated at a higher load factor than originally anticipated.

Favorable economic results for this system can be attributed to the relatively low cost of wood fuels ($8.0/ton) and high annual use of 6920 hours.

Lin (1983) reported that a wood-fired plant with a rated steam production capacity of 4773 kg/h was installed at downtown campus of Charkson College of Technology, New York. In the 1981-1982 heating season, it supplied 55 percent of the steam needs of the downtown campus with a wood fuel consumption of 2857 tons. The supplier charged the price of the wood chips for the first year was $14 - 17/ton at a moisture content of 35 to 40% on wet basis. The wood-fired plant incurred $34,300 in added operating and maintenance costs and reduced the fuel costs by $86,700 during 1981-82. It was concluded that if the wood fuel cost remain the same, then the investment in the wood-fired plant would have a real rate of return (after discounting inflation) in the range of 20 - 23 percent per year.

Junge (1984) reported that Oregon State University has undertaken a project to evaluate the feasibility of a ten megawatt biomass powered, combined cycle power generation facility. The system is intended to burn woody fuels generated from forest fuel crops, forest residues, and from industrial mill residue. He described the "Base System", a list of the assumption made concerning the operation of the facility, and an evaluation of the anticipated emissions of pollutants from the system.

Hamrick (1984) discussed the installation of a three megawatt wood burning gas turbine at Red Boiling Springs, Tennessee. He presented background information on wood burning, wood feed, combustor research, cyclone filter performance and gas turbine selection.

WOOD-FIRED BOILER EFFICIENCY AND ENERGY ECONOMICS

Boiler Efficiency

Heat energy is liberated within the boiler furnace or in the combustion system by the chemical reaction of oxygen with the combustible elements of the fuels. These combustible elements are carbon, hydrogen and sulfur. For any fuel, there is a minimum quantity of oxygen required for complete combustion. The amount of air that contains this minimum quantity of oxygen is termed the theoretical air or stoichiometrical air (Li and Priddy, 1985, and Babcock and Wilcox, 1978). The amount of theoretical air (WTA) in kg per kg of as-fired fuel can be calculated by using the following formula:

$$WTA = 11.51\ C + 34.30\ (H - O / 7.937) + 4.335\ S \qquad (6)$$

The amount of actual dry air (WAA) in kg per kg of as-fired fuel can be calculated using the following expression:

$$WAA = [\{(28.02\ N_2\ (CB + 12.01/32.07\ S))/12.01\ (CO_2 + CO)\}/0.7685] - N/0.7685 \qquad (7)$$

where N_2, CO_2, CO are percentage of nitrogen, carbon dioxide and carbon monoxide in the flue gas.

Since it is impossible to achieve complete combustion with theoretical air, an additional amount of air must be supplied. The air supplied for combustion in excess of that theoretically required for complete oxidation is called excess air. The excess air (EXA) can be calculated as follows:

$$EXA = \{(WAA - WTA)/WTA\} \times 100 \qquad (8)$$

There are two general methods for calculating the efficiency of hot water boiler and steam generating units. These are known as input-output method or direct method and heat loss method or indirect method (ASME Power Test Codes).

The input-output method depends on the measurement of fuel, and water flow, and heat energy content of each. The expression for boiler efficiency (BEFF) by this method is as follows:

$$BEFF = Q_{out} / Q_{in} \qquad (9)$$

or $\quad BEFF = \text{heat energy delivered/heat energy input(fuel)}$

or $\quad BEFF = M_w \ (h2 - h1)/ \ HHV \times FFR \qquad (10)$

where M_w = water flow rate, kg/h

h1 = enthalpy of feedwater at boiler inlet, kJ/kg

h2 = entahlpy of feedwater at boiler outlet, kJ/kg

HHV = higher heating value of fuel, kJ/kg

FFR = fuel feed rate, kg/h

Energy loss from a boiler depends on the mass flow of the flue gases and their temperature. The hydrogen in the fuel burns in the combustion process and forms water which leaves with flue gases in the form of superheated vapor. The moisture in the fuel drastically reduce the boiler system efficiency. The heat loss method requires the determination of various losses. If the boiler energy system losses are in kJ/kg of fuel burned, then the boiler efficiency (BEFF) in heat loss method would be calculated as given below:

$$BEFF = [(HHV - \Sigma Losses)/ HHV] \times 100 \qquad (11)$$

or

$$BEFF = (100 - \Sigma Losses\ in\ percentage) \times 100$$

where

$$Losses = LDG + LMF + LMH + LMA + LUC + LRU + LDF$$

The individual losses can be calculated in kJ per kg of as-fired fuel by the using following equations:

(1) LDG = heat loss due to heat in dry flue gas

$$LDG = WDA\ C_{pg}\ (T_{fg} - T_{ref}) \qquad (12)$$

where

C_{pg} = mean specific heat of the flue gas, kJ/kg °C

T_{fg} = temperature of flue gas, °C

T_{ref} = reference boiler room air temperature, °C

WDA = amount of dry air in kg/kg of as-fired fuel

The amount of dry air (WDA) in kg per kg of as-fired fuel can be calculated using flue gas analysis as follows:

$$WDA = [\{44.01(CO_2)+28.01(CO)+32(O_2)+28.02(N_2)\}/ 12.01(CO_2+CO)] \times (CB + 12.01\ S) \qquad (13)$$

where

CB = kg of carbon burned per kg of as-fired fuel

(2) LMF = heat loss due to moisture in the as-fired fuel

$$LMF = M\ (h_{gG} - h_{fref}) \qquad (14)$$

where

h_{gG} = enthalpy of the superheated water vapor at flue gas temperature, kJ/kg

h_{fref} = enthalpy of the saturated vapor at reference temperature, kJ/kg

(3) LMH = heat loss due to moisture from burning of hydrogen

$$LMH = 9.936\ (H)\ (h_{gG} - h_{gref}) \qquad (15)$$

where

H = kg of hydrogen per kg of as-fired fuel (from ultimate analysis)

h_{gref} = enthalpy of the liquid at reference temperature, kJ/kg

(4) LMA = heat loss due to moisture in the combustion air

$$LMA = W_{md}\ (WAA)\ (h_{gG} - h_{gref}) \qquad (16)$$

where

W_{md} = kg of water vapor per kg of dry air

(5) LUC = heat loss due to unburned carbon

$$LUC = UF\ (33694) \qquad (17)$$

where

UF = unburned carbon in kg per kg of as-fired fuel

(6) LRU = heat loss due to radiation and other losses unaccounted for

These are mainly due to radiation, incomplete combustion, and other unaccounted losses for a wood-fired boiler, and vary from 3 to 5%.

(7) LFD = heat loss due to dust in as-fired fuel

The heat loss due to dust in a wood chip fuel varies from 1 to 2 %.

Energy Aspects

Several kinds of analyses may be used to compare alternatives and to plan the intelligent use of wood energy resources. One such technique is net energy analysis, the explicit study of the energy required and generated by energy supply/demand systems (Energy Research and Development Administration, 1977).

Net energy analysis technique

Net energy analysis and interest in methodologies to perform net energy analysis increased significantly with the passage of the U.S. Federal Non-Nuclear Energy Research and Development Act of 1974, PL-93-577. This law mandates Energy Research and Development Administration (ERDA) to direct comprehensive programs in research, development and demonstration of new energy technologies. It also requires "the potential for production of net energy by proposed technologies at the stage of commercial application be analyzed and considered in evaluating proposals" (Sedlik, 1978).

U.S. Energy Research and Development Administration (1977), defined net energy analysis, to be "the amount of energy resources required by systems that produce, transport, convert and use energy. Consequently, it (net energy analysis) provides a quantitative measure of energy systems and may be used to compare relative worth of competing technologies". In other words, net energy analysis is an accounting of the amount and kind of energy needed by an energy system to produce goods and services, not its value in terms of cost. Energy accounting can be a useful complement to economic analysis at the boundaries of the economic system or activity, where energy flow enters and leave the system. Spreng (1988), concluded that energy resources and waste heat are energy flows that, although essential to economic system or activity, cannot be measured by monetary accounts. To account for these energy flows by using the net energy analysis technique is useful. Energy flows are important to the economic system, and perhaps of even more importance is the effect that energy flows have on energy depletion and the environmental impacts resulting from changing energy flows.

The general methodologies for performing net energy analysis have been outlined by Bullard et al. (1978), Perry et al.(1977) and U.S. Energy Research and Development Administration (1977). The energy system to be analyzed can be defined by a trajectory that begins with an energy resource and goes through several processes to an end use point. The energy analysis characterizes each process by the energy it requires and delivers. The difference between the energy delivered to the end point of the trajectory and all direct and indirect energy used in the process is the net energy delivered. Direct energy input is the energy used for actual operation of the equipment in a process, primarily in the form of gasoline, diesel and electricity. Indirect energy input is the energy invested in manufacture of that equipment. The total energy used to produce goods and services is termed "embodied energy" (Hall et al., 1986). For example, the energy embodied in a tractor includes the energy consumed directly in the manufacturing plant plus all the energy consumed indirectly to produce the other inputs to tractor manufacturing such as steel, labor and capital.

The total of all process energy inputs including embodied energy in a system and all energy required by the system for operation and maintenance is called the "energy subsidy" or "energy from feedback" of the energy system.

There are two general methods of computing the direct and indirect energy inputs of goods and services: process analysis or input - output analysis. Process analysis is more suited to specific disaggregated processes whereas input-output analysis is well suited to aggregated nationwide problems. The detailed description, scope and limitations of these two methods have been discussed by Bullard et al. (1978), and Perry et al. (1977). Tillman (1978), specifically discussed energy analysis in a wood fuel supply and delivery system. Baltic and Betters (1983) presented a generalized trajectory model for a wood energy system, and performed a net energy analysis of a hypothetical fuel wood energy system, to heat the Colorado State Forest Service greenhouses. They assumed fully mechanized operations using purchased equipment and materials in wood energy processes.

Jenkins et al. (1979), performed a net energy analysis for five alcohol fuel production technologies. They considered the fuel consumed in growing the feedstock and the energy available from the by-products. Chambers et al. (1979), discussed net energy analysis of grain based gasohol (10% ethyl alcohol and 90% unleaded gasoline).

Economic Aspects

Economic analyses are important in determining the economic viability and feasibility of alternate energy systems and comparing them with fossil based systems. The most common types of economic analyses for evaluating and ranking alternative energy systems are:

1. Life-cycle costing techniques
2. Payback and break-even analysis
3. Sensitivity analysis

Life-cycle costing techniques

Life-cycle costing techniques can be used in the context of a decision-making process for alternate energy systems to generate economic guidelines. It considers all significant costs and benefits of an energy system over its entire life span. There are four analytical life cycle costing techniques that can be used to evaluate energy systems (Marshall and Ruegg, 1980):

1. Life-cycle costs (LCC)
2. Net saving or net benefit (NS or NB)
3. Internal rate of return (IRR)
4. Saving-to-investment ratio (SIR) or Benefit/cost ratio (BCR)

Life-cycle costs (LCC) method

The life-cycle cost (LCC) method sums all relevant past, present and future costs of an energy system, in present, and or annual value dollars over the economic life of a system. A wood-biomass energy system is cost effective if its life cycle costs are lower than those of the conventional fuel energy systems being used for achieving the same objective of space heating. LCC can be expressed in equation form as follows (Ruegg and Peterson, 1987):

$$LCC = \Sigma_{j=0}^{n} (C_{A1} - B_{A1})_j \ / \ (1 + d)^j \qquad (18)$$

where

A1 = subscript denoting wood energy system being evaluated

C_{A1j} = cost in year j for the wood energy system A1 being evaluated

B_{A1j} = benefits (positive cash flows) in year j for the wood energy system A1 being evaluated

d = discount rate, %

j = time period in years (j = 0, 1, 2,...n)

LCC determines the total cost of the energy investments (less any salvage value), repair and maintenance, replacement, and all other operational costs associated with the energy system over its life period. All cash flows can be determined by one of two methods: the present worth method (PWM) and the equivalent-annual cost method (EACM).

The present-worth method converts all present and future dollars to today's values. The equivalent-annual cost methods converts all past present and future costs to equivalent constant amounts recurring annually over the life cycle of the energy system (Ruegg and Peterson, 1987, Marshall and Ruegg, 1980, Brown and Yanuck, 1980, and The American Institute of Architects, 1982). LCC can be expressed by considering all these fixed and variable costs using the present worth method as follows:

$$LCC = (IP-SP) + EP + MP + RP + TP \tag{19}$$

IP = present value of investment

SP = present value of salvage

EP = present value of fuel energy cost

MP = present value of operation and maintenance cost

TP = present value of taxes, insurance, shelters etc.

Alternatively, equation (21) can also be expressed as follows:

$$LCC = IP - S_n/(1+d)^n + \Sigma_{j=1}^{n} E_j/(1+d)^j + \Sigma_{j=1}^{n} M_j/(1+d)^j + \Sigma_{j=1}^{n} R_j/(1+d)^j + \Sigma_{j=1}^{n} T_j/(1+d)^j \tag{20}$$

where

S_n = salvage value at the end of life period

E_j = fuel energy cost in year j

M_j = operation and maintenance cost in year j

R_j = replacement cost in year j

T_j = taxes, insurance, shelter, etc. cost in year j

Net saving or net benefit method

The net saving (NS) method or net benefit (NB) method determines the net difference in present, and or annual value dollars between two mutually exclusive energy system alternatives. This can be expressed in equation form as follows (Ruegg and Peterson, 1987):

$$N\,S_{A1:A2} = LCC_{A2} - LCC_{A1} \tag{21}$$

where

A2 = subscript denoting fossil based energy system

A1:A2 = subscript denoting the evaluation of wood energy system A1 relative to fossil based system A2

or

$$N\,B_{A1:A2} = \Sigma_{j=0}^{n} \; [(B_{A1} - B_{A2})_j - (C_{A1} - C_{A2})_j] \; / \; (1+d)^j$$

where

C_{A2j} = cost in year j for the fossil based system A2 against which wood energy system A1 is compared

B_{A2j} = benefits in year j for the fossil based energy system A2 against which wood energy system A1 is compared

Internal rate of return method

The internal rate of return (IRR) method measures the rate of return on an investment. It uses the same cost elements as LCC and NS methods but differs from them in its units of measure - percentage rather than dollars, and in the way discounting is performed (Ruegg and Peterson, 1987). It finds the compound rate of interest which will equate an energy system's benefits to its costs, such that net benefits are zero.

$$[\Sigma_{j=1}^{n} ((B_{A1} - B_{A2})_j - (C_{A1} - C_{A2})_j) / (1+i)^j] - (C_{A10} - C_{A20}) = 0 \tag{22}$$

where

C_{A10} = denotes cost of system A1 at the beginning of the period

C_{A20} = denotes cost of system A2 at the beginning of the period

i = interest rate

Saving-to-investment (benefit/cost) ratio method

The saving-to-investment ratio (SIR) or benefit/cost ratio (BCR) determines the ratio of annual benefits or savings to initial investment costs. These can be expressed in equation form as follows:

$$SIR_{A1:A2} = \Sigma_{j=1}^{n} [(C_{A2} - C_{A1})_j/(1+d)^j]/(C_{A10} - C_{A20}) \tag{23}$$

or

$$BCR_{A1:A2} = [\Sigma_{j=1}^{n} ((B_{A1} - B_{A2})_j - (C_{A1} - C_{A2})_j)/(1+d)^j] / (C_{A10} - C_{A20}) = 0$$

<u>Payback method and break-even analysis</u>

Payback analysis is used to determine the number of years in which the initial extra investments for different alternative are paid back. The simple payback (SPB) can bė calculated by dividing total cost by annual saving. The time value of money and future benefits are ignored in this sample payback computation. The minimum solution value of payback (PB) years, can be computed form:

$$\Sigma_{j=1}^{RB} [(B_{A1} - B_{A2})_j - (C_{A1} - C_{A2})_j] / (1+d)^j = (C_{A10} - C_{A20}) \tag{24}$$

If the time value of money is ignored (d=0), the method is known as simple payback (SPB), and if time value of money is accounted for (d= not zero), the method is known as discounted payback (DPB).

Break-even analysis, is of broader scope than payback since its objective is to find the break-even point. A break-even point is the value of a selected variable that will produce equivalence in cost and/ or revenue of alternative energy systems (Smith, 1983).

Sensitivity analysis

Sensitivity analysis examines the relative effects of changes in the costs of one or more components of a life-cycle cost (LCC) analysis. Brown and Yanuck (1980) explained there is almost always some uncertainty in projecting costs associated with the components of the LCC analysis. The process of determining how much the LCC will change as a result of change in one of the input factors, other being held constant, is known as sensitivity analysis. These factors would include life period, investment costs, salvage value, and energy escalation rates.

Cost determinants of wood energy system

The major cost determinants to be considered for wood energy system are as follows (Skog, 1979):

1. capital costs
2. annual maintenance and operating costs and their inflation rates
3. fuel costs

   fuel prices and their inflation rates

   fuel requirements per year as determined by energy requirements and boiler and wood fuel characteristics.
4. property taxes and insurance costs

5. the rate of return required on wood-fired boiler and other equipment

The on-farm wood-fired energy system consists of various operations such as harvesting and chipping of wood energy resources, transportation of wood chips, storage and handling, burning of wood chips and energy recovery by boiler combustion. All these operations involve use of agricultural equipment such as tractors, forage wagons etc., in addition to the boiler system. Edwards and Ozkan (1985), and Hunt (1983) have outlined procedure for computing fixed and variable costs particularly for agricultural equipment. Tillman (1978), and Ruegg and Peterson (1987) have discussed procedure to calculate costs of energy systems.

Arola and Miyata (1981) presented cost and productivity data for a fully mechanized harvesting operation for wood energy. Puttock (1987) discussed the economics of collecting and processing whole tree-chips and logging residue for energy production.

Massey et al. (1981) presented the cost of harvesting whole tree chips from a residual hardwood stand in Louisiana, using a conventional mechanized harvesting operation. They conducted an input-output study of ongoing harvesting operation and used a computer model to evaluate the economic impact of various equipment configurations for the system. The equipment used in the harvesting operation were feller-bunchers, grapple skidders, 448 kw powered whole tree chipper, and 224 kw powered bulldozers. Over the highway diesel trucks pulled chip vans from the harvesting site to the mill.

MATERIALS, EQUIPMENT AND METHODS

The overall analysis of the McNay integrated wood-biomass boiler energy system entailed collecting data on system operations, developing a technological framework, and measuring system efficiencies, thermal energy production delivered, and determining the energy cost of wood using net energy analysis and life-cycle costs analysis. The materials, equipment and methods for this research can be divided as following:

1. technological framework and energy system
2. energy measuring instrumentation and data logging system
3. experimental design
4. test and monitoring procedure

Technological Framework and Energy System

The McNay integrated wood energy system involves various stages to convert wood energy on the ground to energy at the point of actual use for space heating for farmstead applications. The energy system consists of a wood fuel handling system and energy recovery by a boiler system, and ends with the operation of end use devices for space heating (Fig. 7). The main processes in wood fuel handling and energy production are extraction (harvesting, yarding and chipping

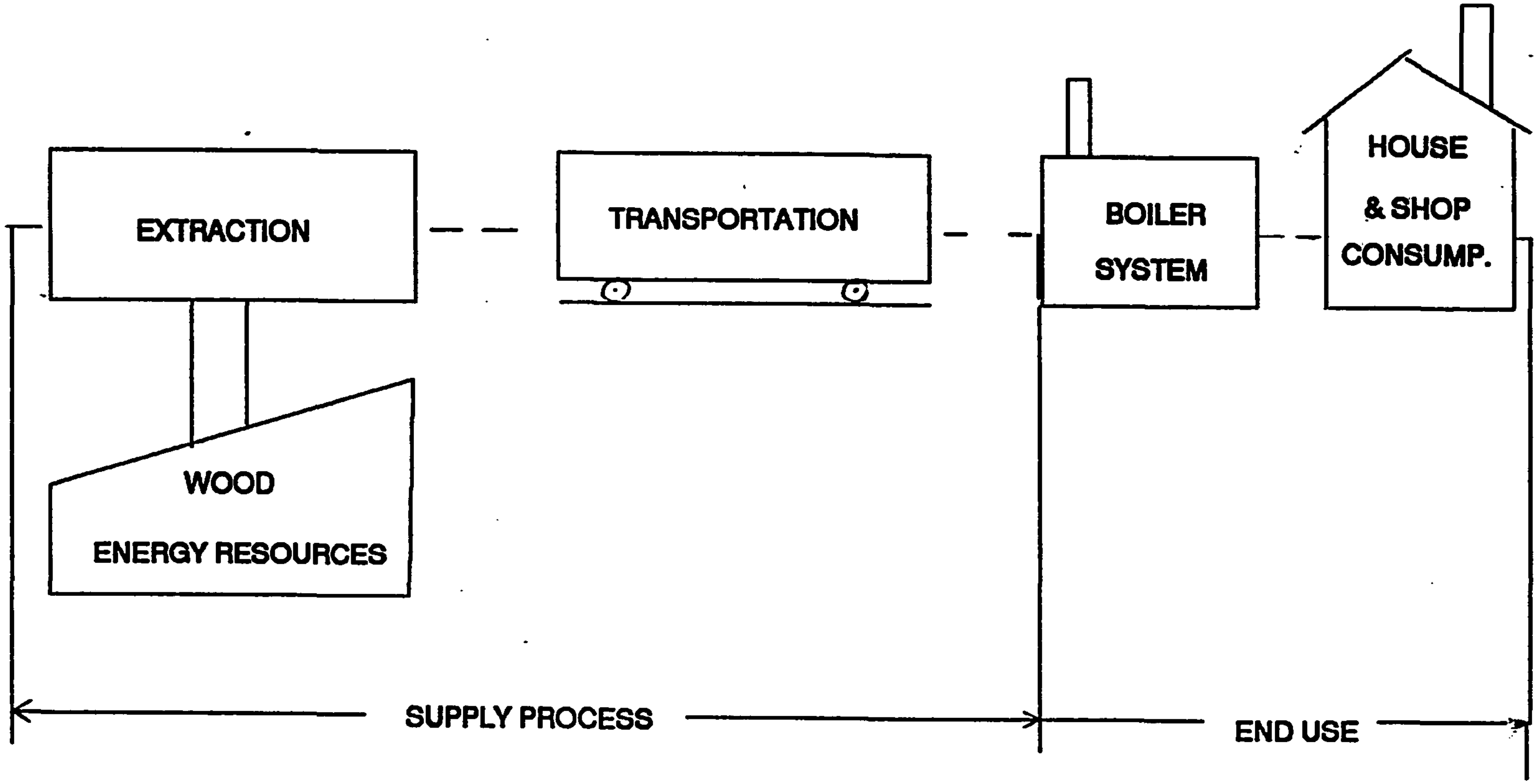


Figure 7. Schematic of the McNay integrated wood energy system

the wood resources), transportation of wood chips, storage, automatic burning of chips in the combustion chamber of the boiler system, and hot water delivery for space heating through an insulated underground piping and heat exchange system. Fig. 8 illustrates the various processes and subprocesses involved in the McNay wood energy system. The wood fuel handling and energy production system is semi-mechanized, and uses existing equipment, materials and services available at the farm for energy production.

Wood fuel production and handling system

There are 64 ha of existing woodland and 22 ha are being planted as an energy plantation. The whole tree above the ground, including wood, bark and foliage, is utilized to make wood chips. Improved management practices are being demonstrated on the existing woodland area at McNay. These involve inventory control, thinning, pruning, planting, weed control and harvest. The existing stand consists primarily of elm, hickory, maple and oak trees.

The extraction process involves cutting of trees by chain saws (Figs. 9 & 10), skidding of cut trees towards the field located chipper (Fig. 11), and chipping with the tractor operated chipper (Fig. 12). In all these operations human power is being used for cutting, skidding and feeding the whole tree into the chipper. The chipper blows the chips directly into a chip van towed by a tractor

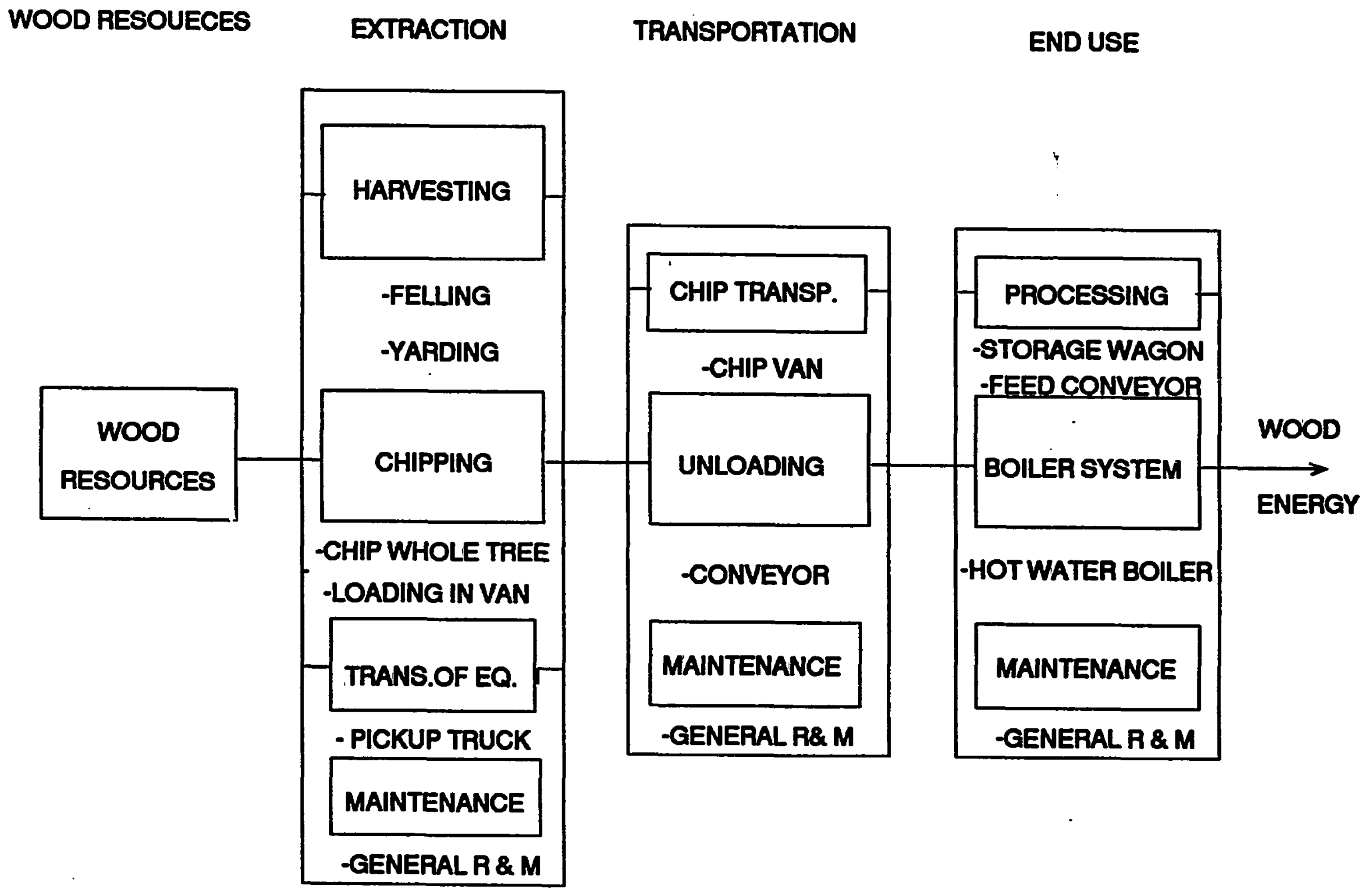


Figure 8. Various processes and subprocesses involved in McNay wood energy system

Figure 9. Harvesting operation using chain saw

Figure 10. Yarding operation using chain saw

Figure 11. Skidding operation of cut tree towards the field located chipper for chipping operation

Figure 12. Feeding the whole tree into the chipper for chipping

(Fig. 13). Usually 3 workers handle this extraction operation. One person drives the pickup truck and transports two chain saws and other supplies into the timber area. One person drives a tractor, towing a chip van and the other person drives a tractor with the rear mounted chipper.

In the transportation process, the loaded chip van is towed by a tractor to the unloading area outside the boiler room (Fig. 14). The chip van is unloaded into a storage wagon by means of a tractor operated conveyor (Fig. 15).

Alternatively, the chipping operation can also be performed right outside the boiler room by transporting wood logs from the field (Fig. 16). The chipper can blow chips directly into the storage wagon (Fig. 17).

The wood chips from the storage wagon are automatically fed to the boiler combustion chamber by a conveyor and a gravity feed system (Figs. 18 and 19). The hot gases from the combustion chamber travel through the boiler, which transfers the heat to produce hot water. Insulated underground piping carries hot water to heat exchangers for space heating in the farm residence and farm shop.

Wood-fired boiler system

The McNay wood-fired boiler system consists of an inclined step grate pile burning combustion system with primary and secondary air

Figure 13. The chipper blowing the chips into a chip van

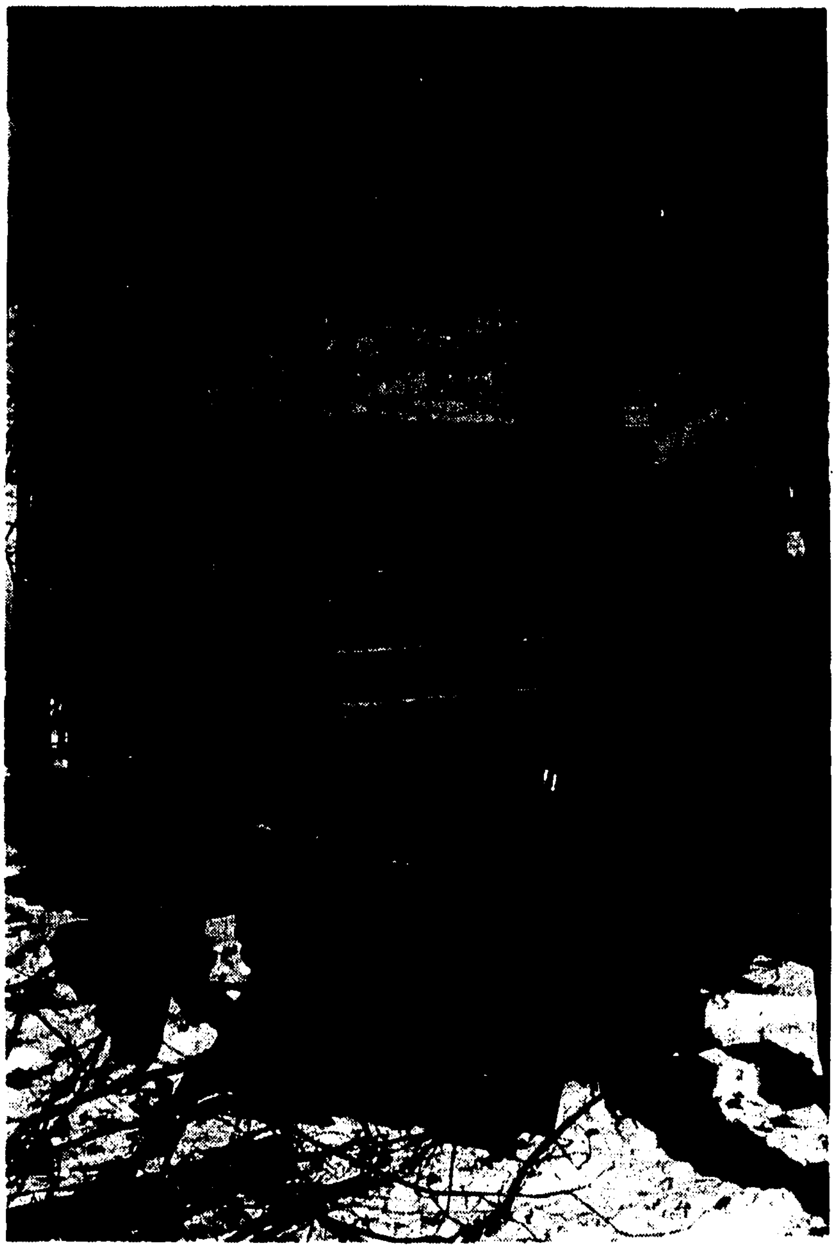


Figure 14. Transportation of chips in the chip van from field to the boiler room

Figure 15. Transfer of chips from the chip van into the boiler room storage wagon

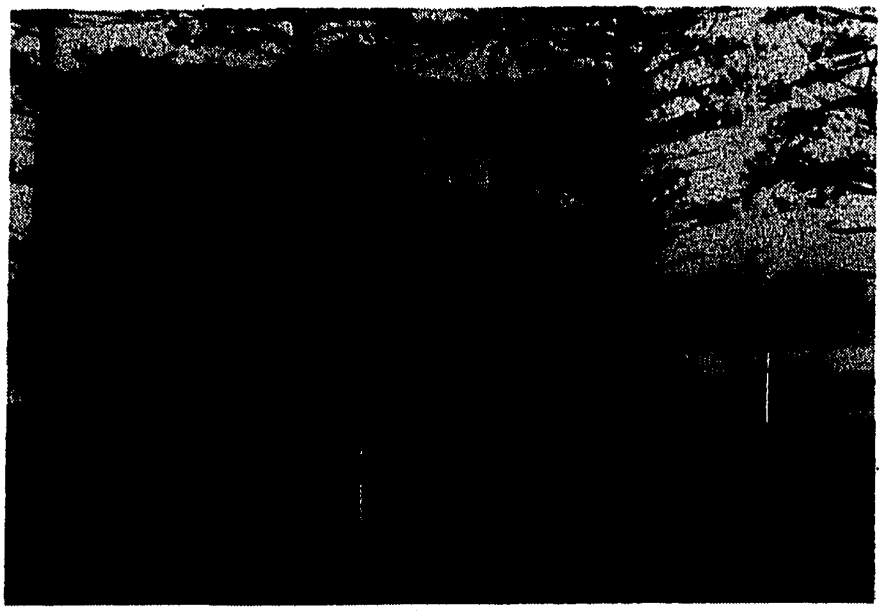


Figure 16. Transportation of wood-logs from the field for chipping to be performed right outside the boiler room

Figure 17. The chipping blowing chips directly into the boiler room storage wagon

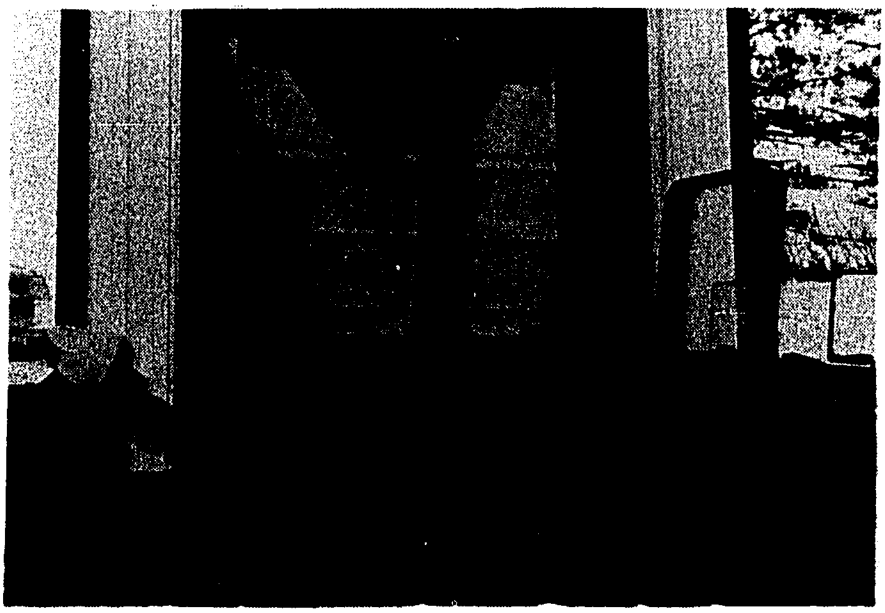
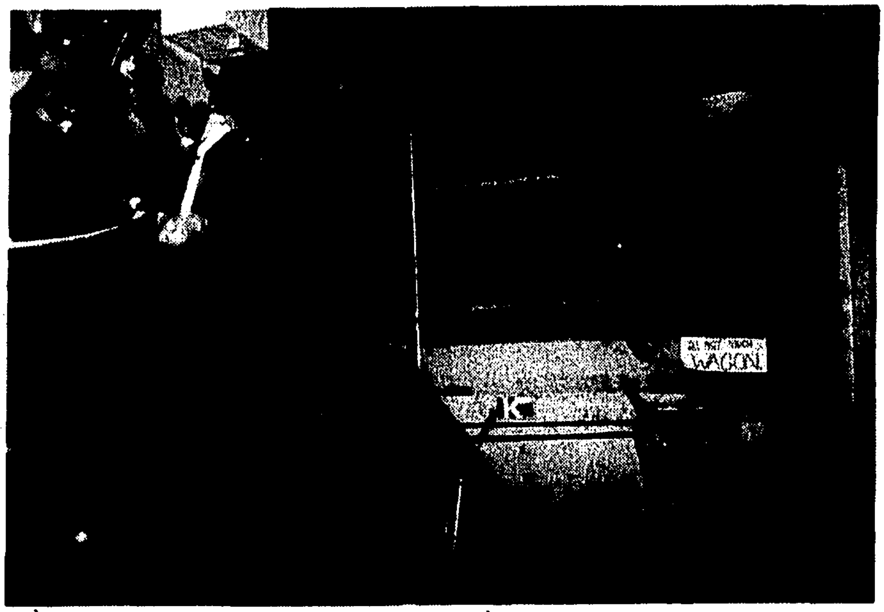
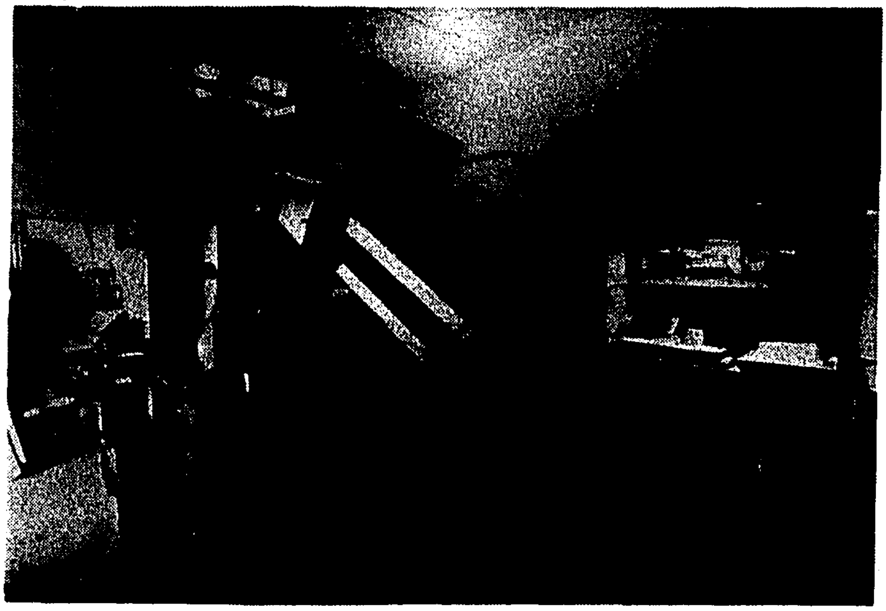


Figure 18. Automatic boiler feed conveying system

Figure 19. Transfer of chips from storage wagon into the boiler combustion chamber by conveyor and gravity feed mechanism


WAGON



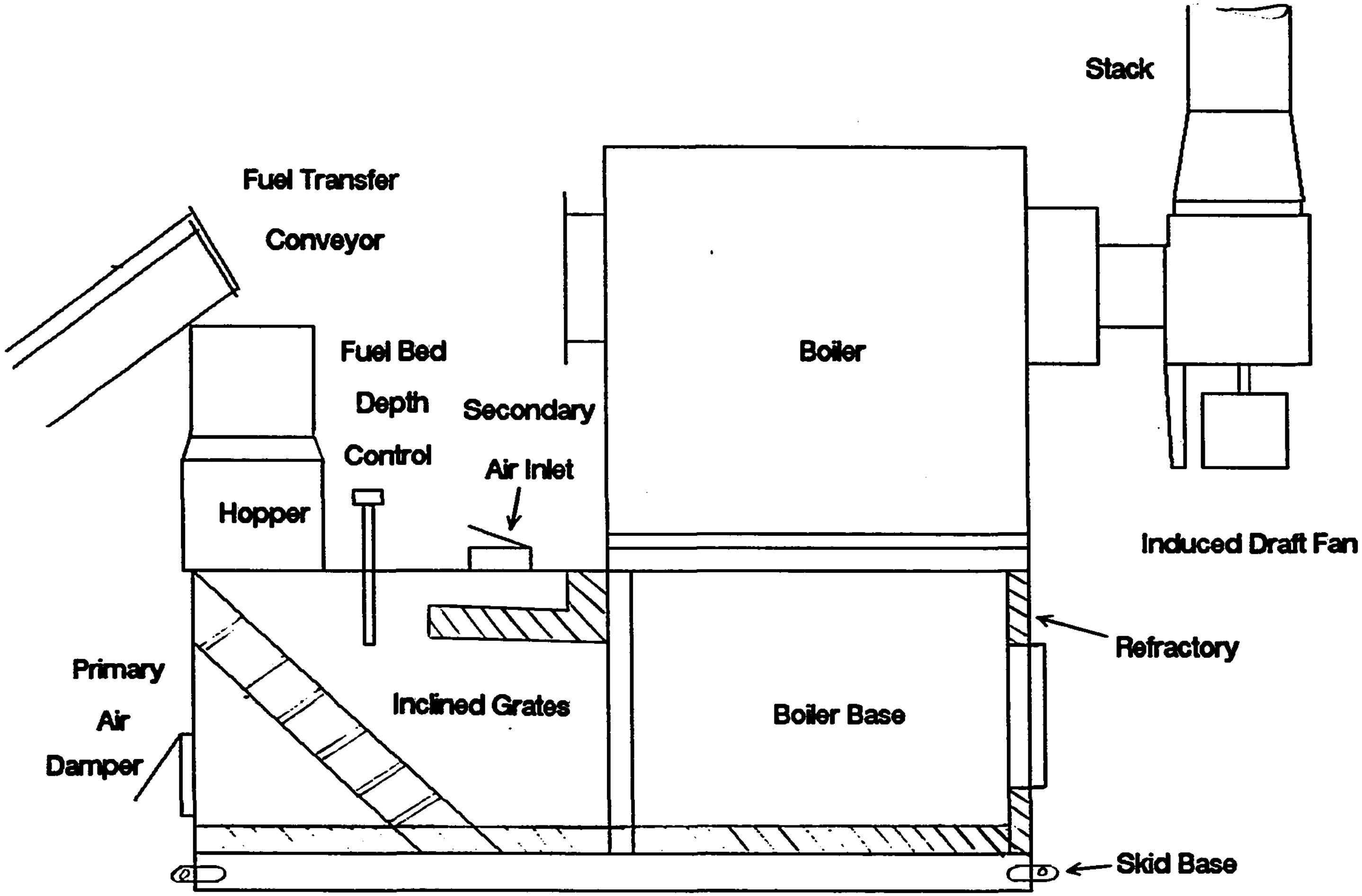


Figure 20. Schematic diagram of McNay wood-fired boiler system

inlets, a horizontal firetube boiler, a draft fan, stack, control panel and a boiler skid base with ash door (Fig. 20). The boiler system has a thermal energy capacity of 530,000 kJ/hr while burning green wood chips. The main specifications of the boiler system are listed in Appendix A.

A carbonized fuel bed is established on the inclined grates of the pile burning system, which heats the raw fuel flowing by gravity onto the grates. Combustible gases are distilled off the fuel, mixed with preheated secondary air, ignited and burned in the combustion chamber. A standing column of raw fuel is maintained in the feed hopper by a level control which activates the fuel transfer feed conveyor from the storage wagon.

The firing rate is controlled from the temperature setting on the boiler system, which positions the primary air damper to control the rate of combustion. The hot gases from the combustion chamber travel through the boiler tubes, which transfer heat to produce hot water (Fig. 21). The cooled flue gases are then drawn through the induced draft fan and vented to atmosphere. Insulated underground piping (Figs. 22 & 23) carries hot water to heat exchangers for space heating in the farm house (Fig. 24), and farm shop (Fig. 25).

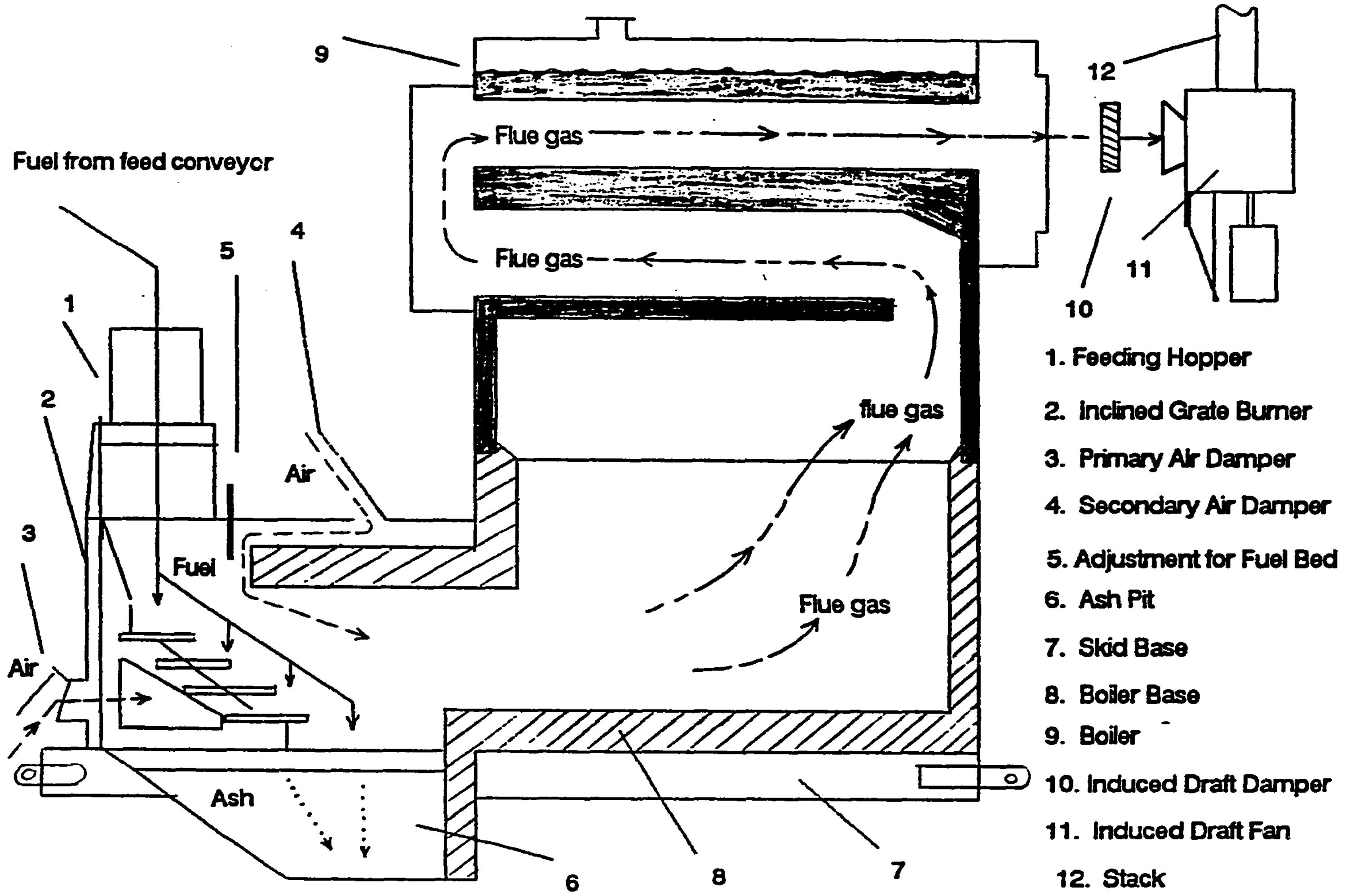


Figure 21. Flow pattern of fuel, air and hot flue gases in the boiler system

Figure 22. Insulated water supply and return plastic pipes

Figure 23. Underground hot water distribution piping system used at McNay wood energy system

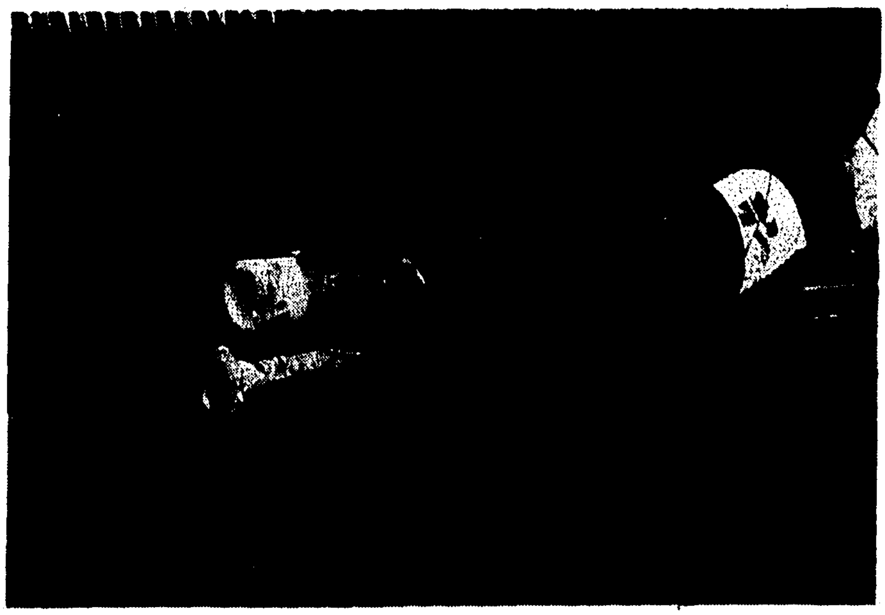
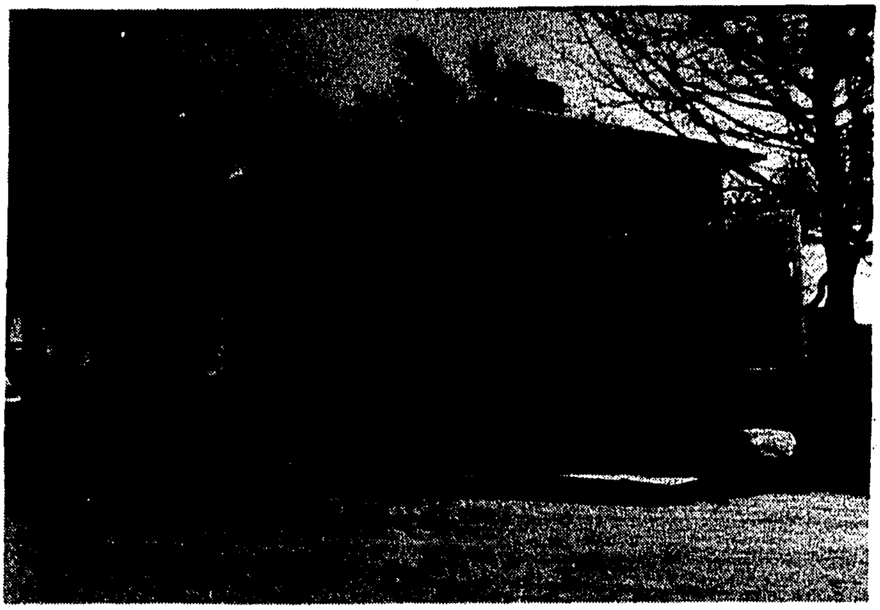
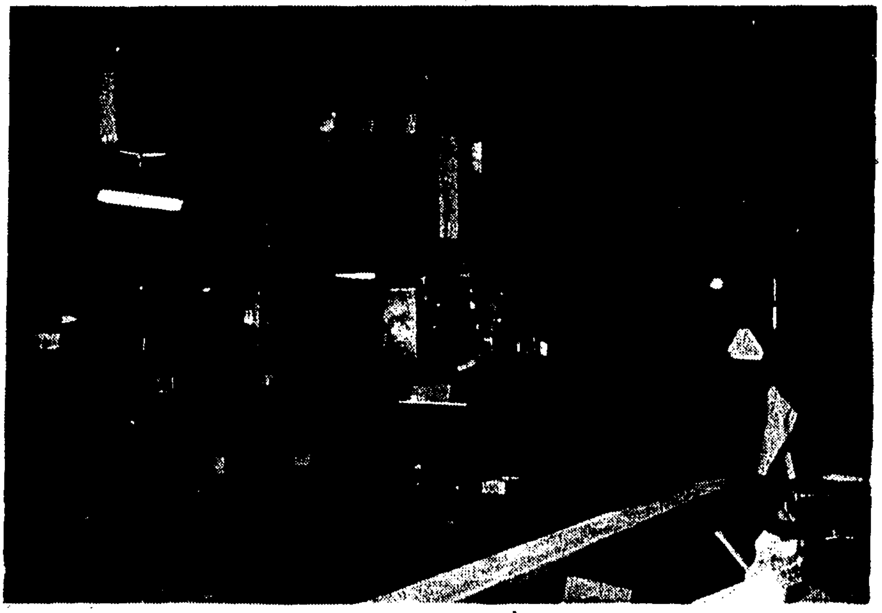


Figure 24. Farm house where wood energy was supplied for space heating

Figure 25. Farm workshop where wood energy was supplied for space heating





Energy Measuring Instrumentation and Data Logging System

Measurements and experimentation are closely related to the development of science, research, engineering design, and the manufacturing of goods (Tse and Morse, 1989). Reliable experimental measurements can be made by carefully using precise electronic sensors or instruments to collect and record data.

One of the objective of this study was to monitor the amount of wood energy delivered for space heating for farmstead applications during the winter heating season 1989-90. The energy requirement for space heating varies with the environmental conditions and human thermal comfort inside the building, during day and night hours. It was impossible to measure energy flows in this system without developing some kind of instrumentation and data logging system or data acquisition system.

Several criteria were considered and adopted in developing the energy measuring instrumentation and data logging system, as follows:

1. to collect and record all energy flow time series data in electronic format and as required by ASME Power Test Codes, to measure boiler efficiency both by input-output and heat loss methods.

2. to develope a relatively simple, cost-effective and reliable system for continuous recording of thermal energy data to be permanently installed for future energy monitoring.

Data logging system

The data logging system is a data acquisition system that measures the analog inputs, translates the results into the digital domain, and store the data for analysis. Fig. 26 illustrates the block diagram of a data logging system. A data acquisition system can be defined as an electronic instrument or group of interconnected electronic hardware items, dedicated to the measurement and quantization of analog signals for digital analysis or processing (Vandoren, 1982).

All the instruments and equipment used in the data logging system are portable, with an additional option of shifting to battery power in case of electric power failure. The main concern was that electric power fails more frequently on the farm than in cities, so that the whole system should automatically shift to battery power and ensure retention of all of the data and continuous smooth functioning of the data logging system.

The PL-1000 unit (from Elexor Associates, New Jersey) was utilized to handle input channel selection, (analog multiplexer), signal amplification or signal conditioning, and analog-to-digital

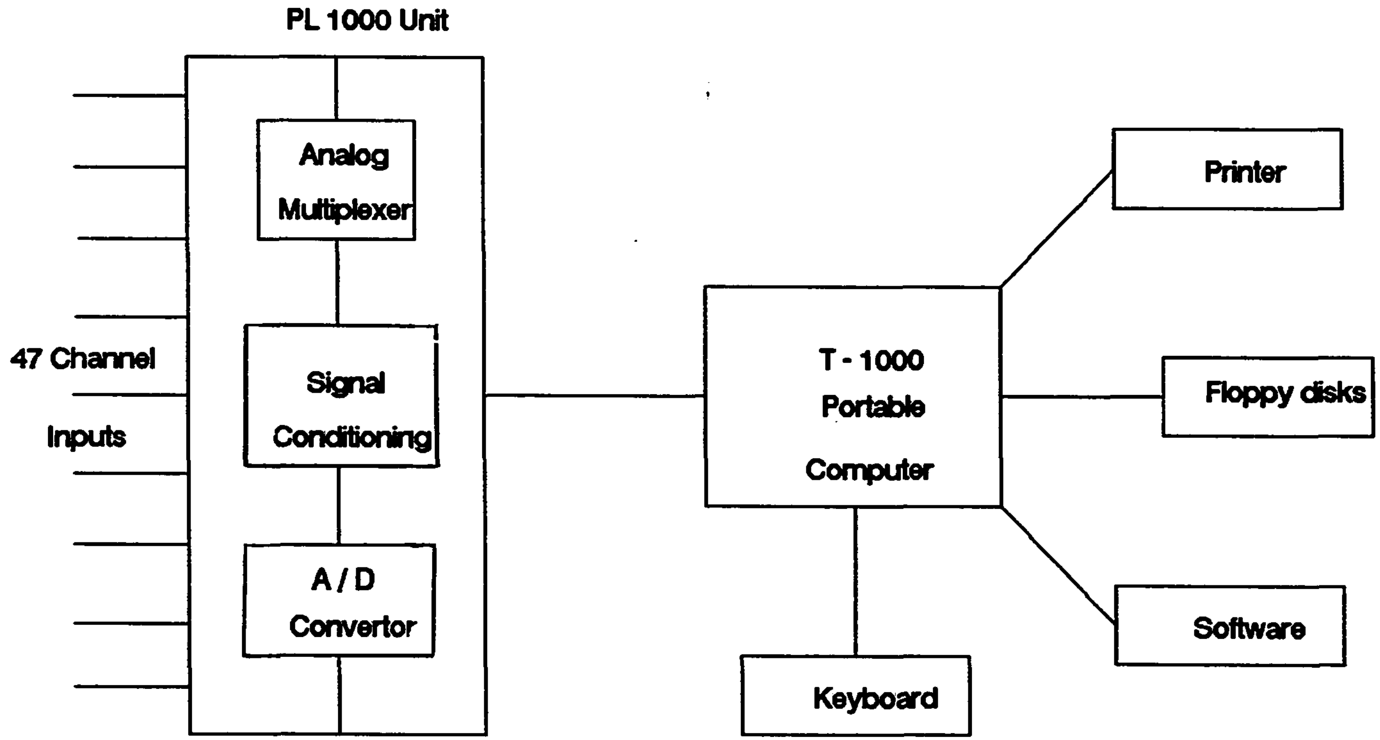


Figure 26. Block diagram of data logging system

conversion of the selected channels. The PL-1000 unit can handle 16 (0-15) channels and its capability was increased by adding analog and digital expansion boards. The PL-1000 unit was connected to a Toshiba T-1000 portable computer through a standard RS-232 interface. The basic software program was operated on the T-1000 computer to collect and record data using the PL-1000. Data can be displayed on the computer screen, or recorded on the 89 mm floppy disk or printed using any parallel interface printer.

The channel scan time, display time on screen or recording time on floppy disk or printing interval on the printer can be made different according to the requirements of gathering data and its subsequent analysis. The data recording time varies from a fraction of a second to minutes or hours. Data were transferred from 89 mm floppy to 133 mm floppy disk and a Fortran program was used to manipulate and analyze that data.

The wood-fired boiler system was installed some distance away from the farmstead due to safety reasons. The house is about 60 meters away from the boiler room, whereas new workshop, old workshop and grain bin are situated about 100, 25, and 20 meters respectively away from the boiler system. Instead of running lengthy thermocouple extension wires from one data logger, it was found to be more economical to use two sets of data loggers, one in the boiler room (Fig. 27) and the second in the house (Fig. 28).

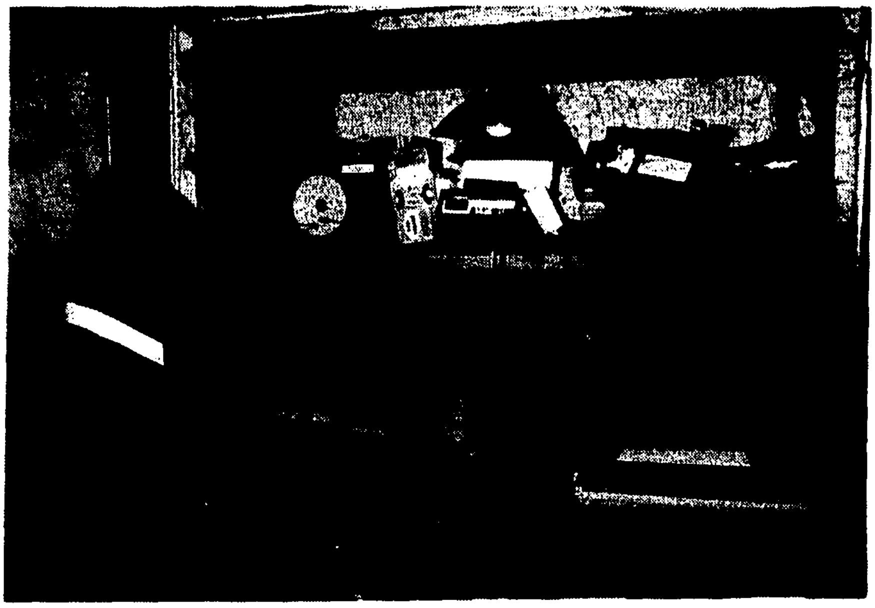
<u>Energy measuring data</u>

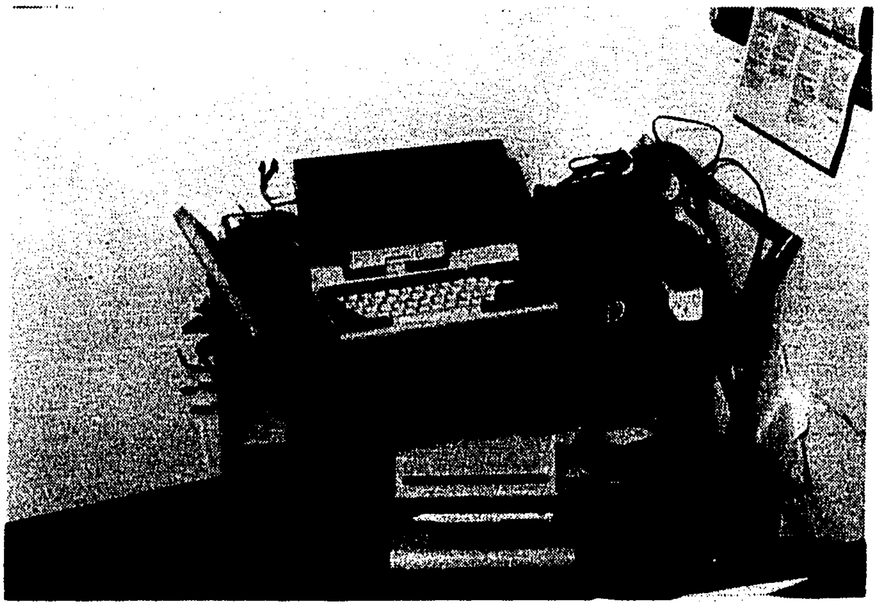
The various energy measuring and monitoring instruments fitted to or used with the wood fired boiler, provided the following data:

* fuel and combustion air temperature
* moisture content of wood-chip fuel
* mass of wood-chip consumed
* temperature at inlet and outlet of house water line connection to boiler
* temperature at inlet and outlet of shop water line connection to boiler
* volume of water flows to house and shop
* flue gas temperature at boiler rectangular duct (a head of induced draft fan)
* volume of flue gas flow at boiler rectangular duct (a head of induced draft fan)
* stack gas temperature
* volume of stack gas
* flue gas analysis (percent CO_2, O_2, and CO) at boiler rectangular duct (a head of induced draft fan)
* stack gas analysis (percent CO_2, O_2, and CO)

Figure 27. Instrumentation and data logging system in the boiler room

Figure 28. Instrumentation and data logging system in the house





* temperature at inlet and outlet of heat exchanger for space heating
* Ambient conditions such as air temperature, wind velocity, and air relative humidity
* indoor or room conditions such as air temperature, air relative humidity
* thermal energy delivered to the house and shop
* thermal energy distribution losses

Energy measuring instruments and equipment

Temperature measurements All temperature were measured by using type K Chromel-Alumel thermocouples. OMEGACLAD thermocouple wire 304-K-MO-188 (from OMEGA Engineering, Inc., Stamford, CT) was used in manufacturing thermocouples of different length from 25 mm to 1000 mm for accurate measurements at different points or location in the boiler system. The OMEGACLAD is a solid stainless steel sheathed cable containing thermocouple wires which are insulated from each other and from the sheath metal by highly compacted ceramic insulation of magnesium oxide. Grounded junctions of the thermocouples were made in order to get faster response time for temperature measurements. Compression fittings were used for securing and sealing the thermocouples in pipes and tanks of the boiler system.

The basic thermocouple circuit has both a measuring junction and a reference junction. When a thermocouple is placed to measure a temperature, it converts temperature difference into an electromotive force called Seebeck voltage. The temperature of the measuring junction can be determined by knowing the temperature at the reference junction and by measuring the voltage (Fig. 29).

The computer software compensation method was used to determine the temperature at the reference junction of the thermocouple. A thermistor, whose resistance is a function of temperature, was used to measure the thermocouple reference junction temperature.

The thermistor is a very sensitive non-linear temperature measuring device. This temperature-resistance relationship can be approximated by using the Steinhart-Hart equation (Kerlin and Shepard, 1982, and McGee, 1988):

$$Tt = [\ a + b \ln R_T + c\ (\ln R_T)^3\ ]^{-1} \qquad (25)$$

where

Tt = temperature in degree Kelvin

R_T = thermistor resistance

a, b, & c = curve fitting constants

Three thermistor (from Radio Shack, Cat. No. 271-110) and three fixed resistor were utilized to achieve better linearization (Fig.

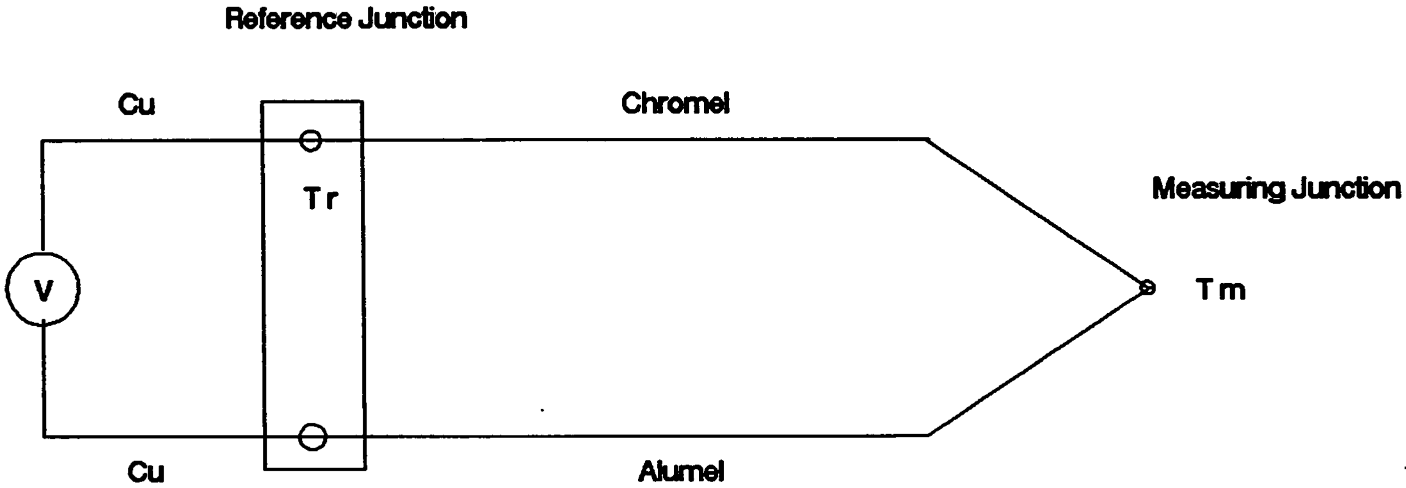


Figure 29. Thermocouple circuit for measuring temperature

30). The Steinhart-Hart equation for this Radio Shack thermistor was determined to be:

$$Tt = [8.8066\ E\text{-}4 + 5.8197\ E\text{-}4(\ln R_T) + 2.301\ E\text{-}6(\ln R_T)]^{-1} \quad (26)$$

In Fig. 30, the three thermistors are identical and three resistors are identical. The thermistor voltage was determined as follows:

$$Vt/Vin = (R_T + R)R_T/(R_T + R)^2\ R_T + R\{2R_T(R_T + R) + (R_T + R)^2\} \quad (27)$$

where

Vt = thermistor voltage

Vin = input voltage

R_T = thermistor resistance

R = resistance of fixed resistor

The constant input voltage (Vin) of 5 volts was supplied to the thermistor circuit. The relationship between thermistor voltage (Vt) and resistance was determined to be as follows:

$$R_T = -\ 59.87281 + 150.9412\ (Vt) - 143.8986\ (Vt)^2 + 70.39916(Vt)^3 - 16.62504\ (Vt)^4 + 1.592049\ (Vt)^5 \quad (28)$$

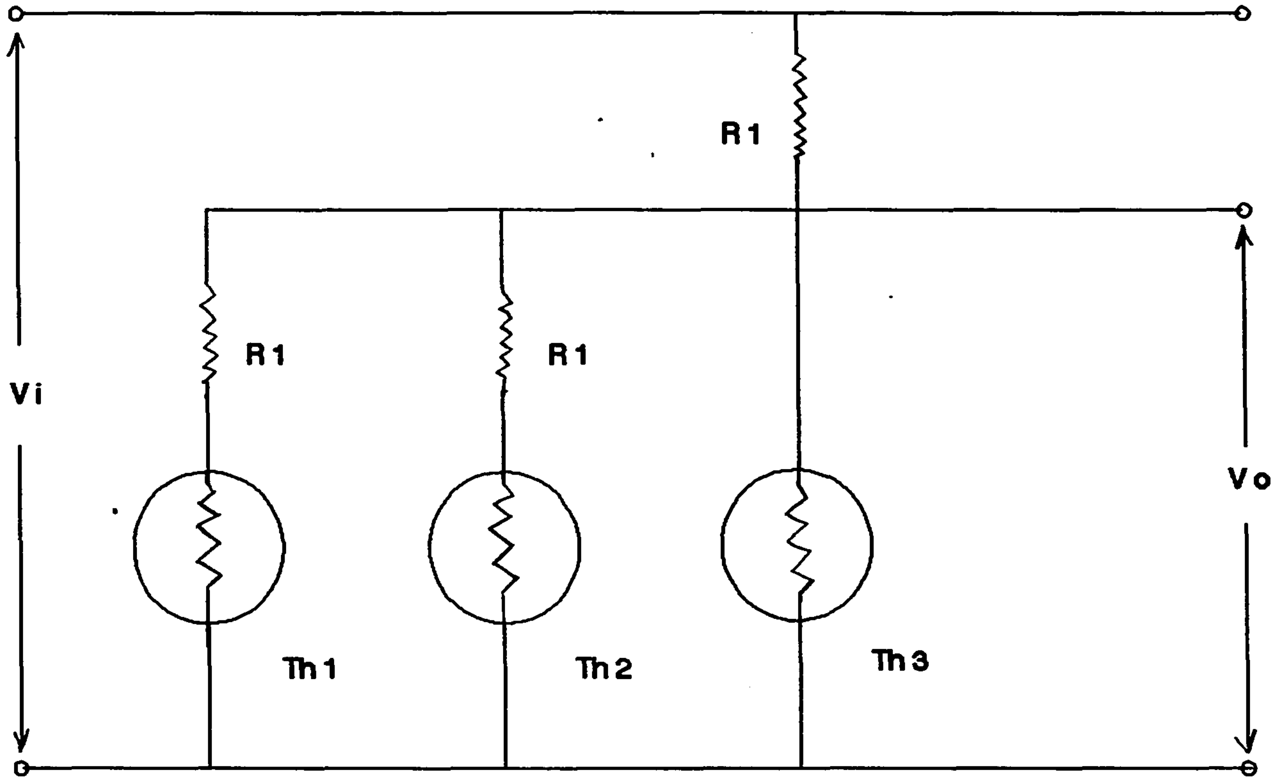


Figure 30. Thermistor circuit for linearization

The thermocouple reference junction voltage (Vref) was estimated from the relationship:

$$Vref = 6.335648\ E{-}05 + 3.942723\ E{-}02(Tt) + 2.544203\ E{-}05(Tt)^2 - 1.96795\ E{-}07(Tt)^3 + 5.321433\ E{-}10(Tt)^4 - 3.592125\ E{-}12\ (Tt)^5 \quad (29)$$

This thermocouple reference junction temperature was corrected by computer Fortran software while analyzing data as follows:

1. measure voltage across thermistor, which is equivalent to reference junction voltage, Vref.
2. measure voltage (v) across thermocouple (Fig. 29) and subtract Vref to find measuring junction voltage (Vm) and convert Vm to measuring junction temperature(Tm).

The thermocouple voltage was converted to temperature by using following polynomial equation for K type thermocouple (OMEGA, 1989):

$$T = 0.226584602 + 24152.109\ X + 67233.4248\ X_2 + 2210340.682\ X^3 - 860963914.9\ X^4 + 4.83506\ E{+}10\ X^5 - 1.18452\ E{+}12\ X^6 + 1.38690\ E{+}13\ X^7 - 6.33708\ E{+}13\ X^8 \quad (30)$$

where

T = temperature in ° C

X = thermocouple voltage

All thermocouples were individually tested and calibrated for accuracy before being permanently installed and hooked up to the data logging system.

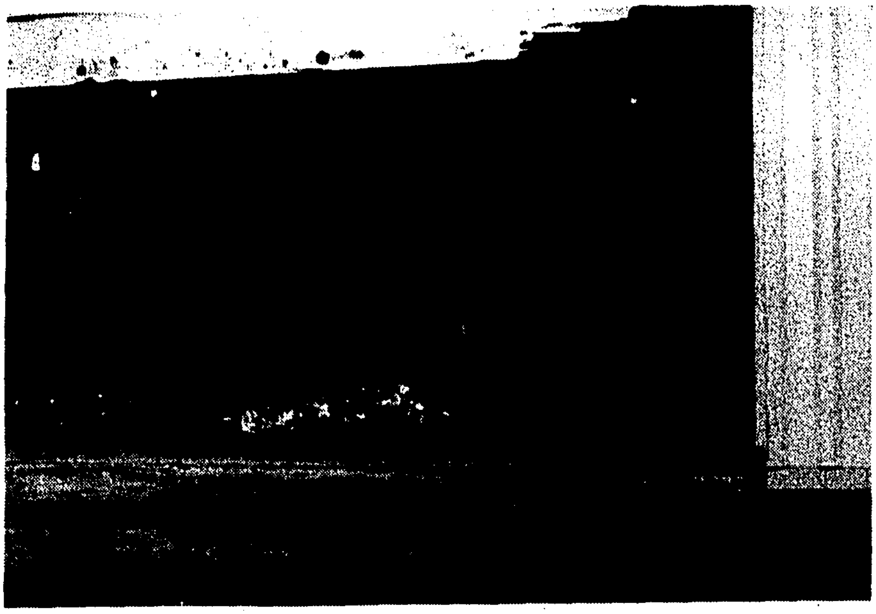
Mass of wood chip fuel A forage wagon (4.88 m X 1.83 m X 1.83 m) was used to store the wood chip fuel in the boiler room. The maximum storage capacity of this wagon was about 5 metric tons of wood chips. Four S-type load cells LCCB-10K (from OMEGA Engineering, Inc., Stamford, CT) were installed in a circuit beneath the wagon to measure the mass of fuel consumed (Fig. 31). The load cell had a rated output of 3 mv/v and requires excitation voltage of 10 Vdc. The OMEGA DP-88 precision strain gage indicator with excitation voltage 10-15 Vdc, was used to measure the load cell signal and to display the mass of fuel in kg. The analog signal from the indicator was also fed into the data logging system.

Flue gas analysis In flue gas analysis, carbon dioxide, oxygen and carbon monoxide were separately measured using Bacarach analyzers. The accuracy of flue gas analysis was also checked by using Orsat apparatus.

Water flow measurements There are three hot water supply lines and three cold water return lines for house, shop and grain bin respectively. Three booster pumps were used; one in each hot water supply line (Fig. 32). A 0.24 kw pump was installed in the grain bin line and 0.56 KW were installed in the both house and new workshop

Figure 31. Load cells installed underneath the wagon to measure mass of wood chip fuel consumed

Figure 32. Three booster pumps were used, one in each hot water supply line of house, workshop and grain bin



lines. Turbine flowmeters FTB 5000 series (from OMEGA Engineering, Inc. Stamford, CT) were permanently installed in all these lines (Fig. 33). Turbine flowmeters are volumetric flow-rate sensing meters with a magnetic stainless steal turbine rotor suspended in the flow stream. Rotational speed of the turbine is proportional to water velocity and to volume rate of water flow.

Flue gas flow measurements Pitot tubes with manometers were used to measure the flue gas velocity (Fig. 34). Three set of pitot tubes with manual traverse units were permanently installed in a rectangular duct ahead of the induced draft fan, and another set of three were installed in the round stack pipe. A traverse reading pattern was adopted in order to obtain the average velocity of the flue gas in both round and rectangular ducts, as recommended by ASHRAE Handbook (1985).

Fuel moisture measurements Wood chip fuel moisture was measured on-site with an infra-red moisture meter. The moisture meter takes about 5 minutes to measure the moisture content of the wood chips on a wet basis. The moisture of the wood chip fuels was also determined by oven drying samples for 24-36 hours.

Figure 33. Boiler hot water supply and return lines (Figs. a and b). Turbine flowmeters were installed in supply lines. Thermocouples and display type thermometers were installed in both supply and return lines

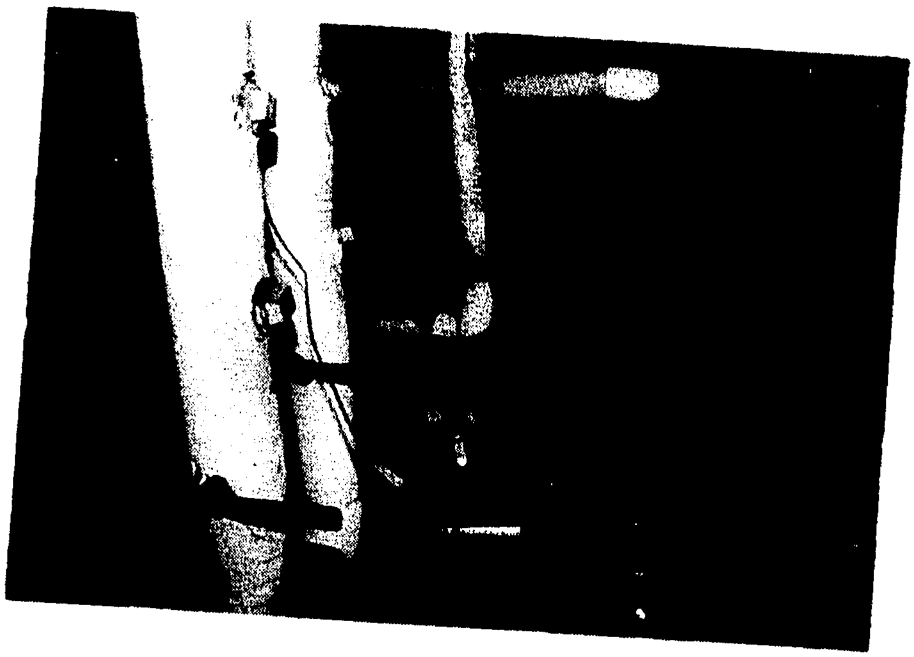
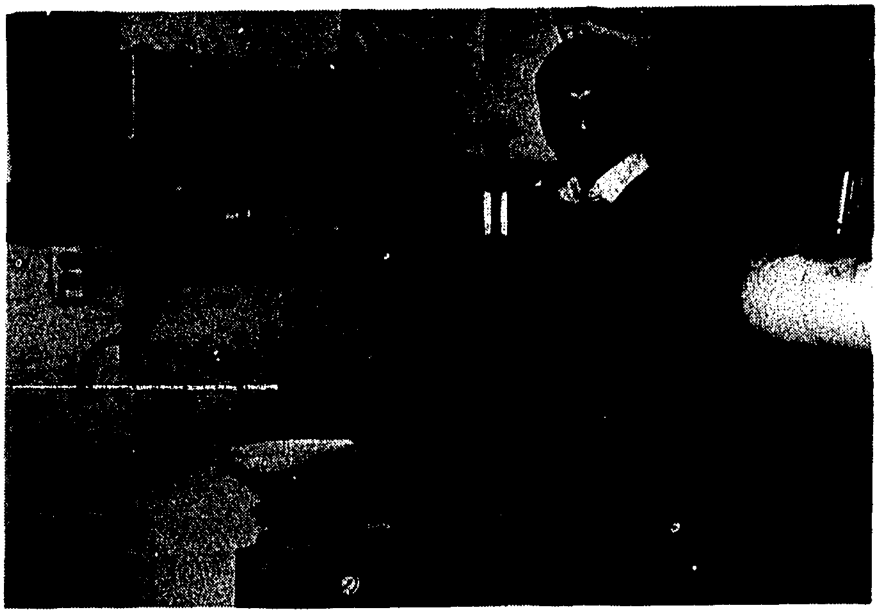


Figure 34. Pitot tubes installed with manual traverse units to measure flue gas flow (Fig. a). Combination inclined/vertical manometers were used with pitot tubes (Fig. b). Bacharach gas analyzers were used for flue gas analysis



Experimental Design

The objective of the experimental investigation was to determine the performance characteristics of the wood-fired boiler energy system while burning green wood chip fuel. The interest was to determine and specify the operating conditions that maximize the wood-fired boiler system efficiency. Based upon experience, three controllable (independent) variables were chosen that influence the dependent variable, boiler system efficiency.

The independent variables were (Figs. 35 & 36):

PAD = primary air damper opening

SAD = Secondary air damper opening

DFB = Depth of fuel bed

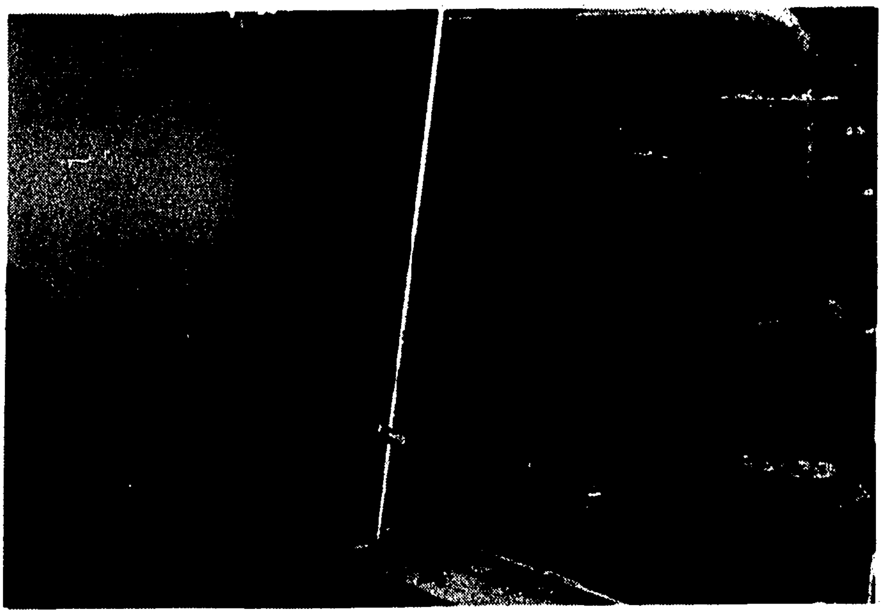
The dependent variable was:

BEFF = wood-fired boiler system efficiency

The PAD controls the intensity of the combustion or rate of combustion by allowing combustion air to pass through the fuel bed and distill off the combustible gases. The SAD controls the amount of additional combustion air required for complete combustion of distilled gases. The DFB controls the wood chip feed rate, which varies with fuel moisture content, and size and density of the chips. All these variables control the energy output of the boiler system. The quadratic central composite design (CCD) was employed in the

Figure 35. Primary air damper

Figure 36. Secondary air damper and depth of fuel bed adjustment



boiler system performance test. This experimental design has been discussed by Box and Draper (1988), Montgomery (1984), and Cochran and Cox (1957).

The model for this quadratic central composite design is as follows:

$$Y = B_o + \Sigma_{i=1}^{K} B_i X_i + \Sigma^{K}_{i=1} B_{ii}X_i^2 + \Sigma^{K}_{i<j} B_{ij} X_iX_j + E \quad (31)$$

where:

Y = boiler system efficiency

B_o = intercept

B_i = linear coefficient relating boiler efficiency to the ith input variable

X_i = level of ith input variable, i = 1, 2, 3 =K

X_1 = PAD, X_2 = SAD, X_3 = DFB

B_{ii} = quadratic coefficient for the ith variable

B_{ij} = Interaction coefficient for the interaction of variables i and j

E = random error

Fig. 37 shows the configuration of the central composite design for $K = 3$. It consists of factorial points $F=2^K = 8$, axial points $2K = 6$, with a radius of each axial point $a = (F)^{0.25} = 1.682$, and central points $2K = 6$. In this way the experimental design requires a total of 20 combination of tests. Table 5 shows the variable values chosen for each test, both in original and coded form. These tests were performed in completely randomized order.

Test and Monitoring Procedure

The wood-fired boiler testing and monitoring procedure can be divided into 4 different parts:

1. extensive pretesting
2. performance testing
3. extended period testing
4. continuous monitoring

Throughout the test and monitoring period during the winter season, the variation due to fuel moisture content, species, age of the tree, part of the tree, etc., were kept to minimum (or constant) by using the same moisture fuel and same kind of species. The fuel moisture content was measured within 300 seconds with an infra-red moisture meter. The fuel samples were also oven dried, and it was found that the infra-red fuel moisture readings were 2-3% lower than the oven dry method. Similarly the boiler temperature and pressure setting for the hot water boiler were kept constant during the test and for the rest of the monitoring period.

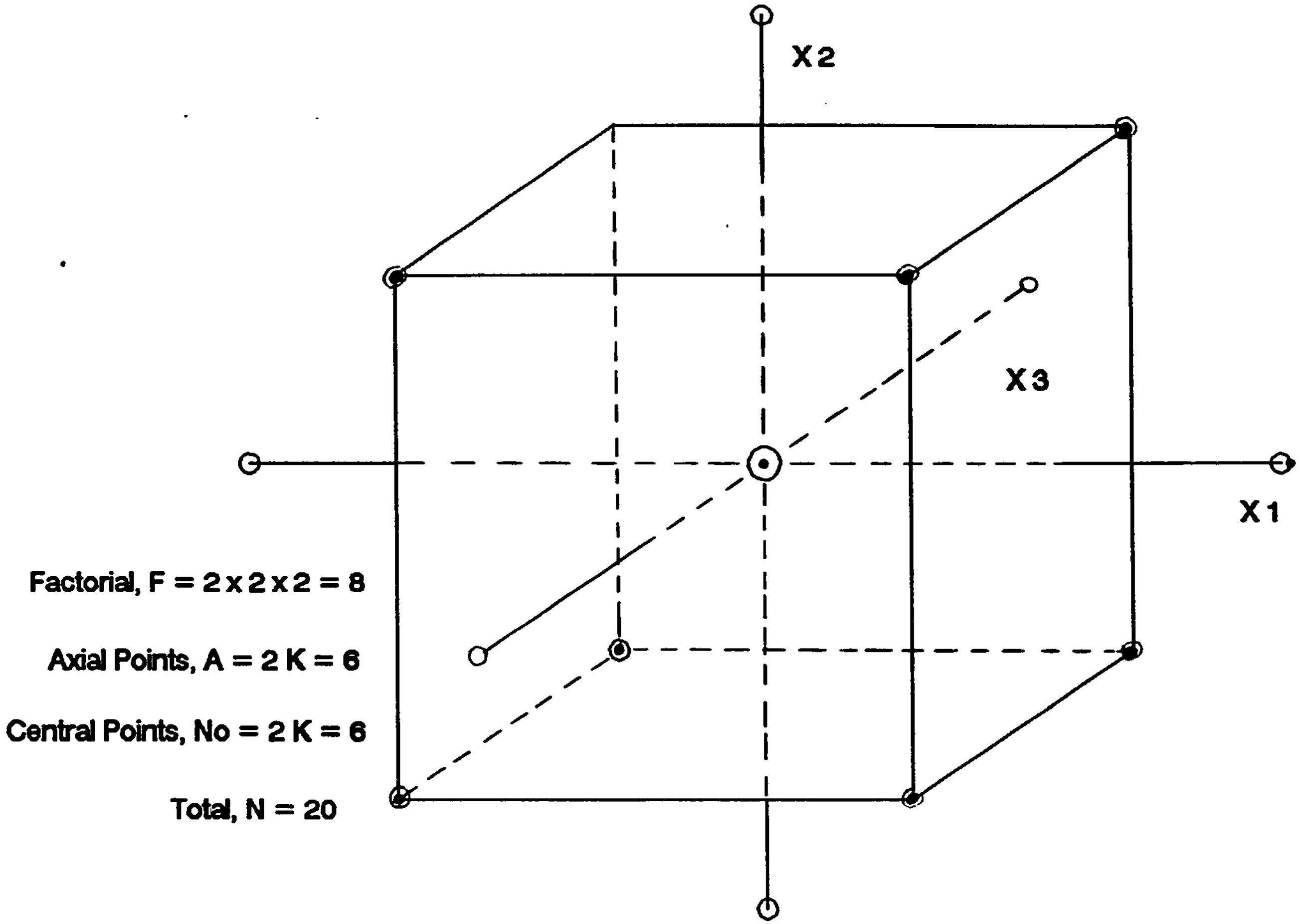


Figure 37. Configuration of quadratic central composite design

Table 5. Test operating input variables both in original and coded form

Test #	Original Variable, mm PAD	SAD	DFB	Coded variables X1	X2	X3
1	51	13	64	-1	-1	-1
2	51	13	114	-1	-1	1
3	51	38	64	-1	1	-1
4	51	38	114	-1	1	1
5	102	13	64	1	-1	-1
6	102	13	114	1	-1	1
7	102	38	64	1	1	-1
8	102	38	114	1	1	1
9	76	25	89	0	0	0
10	76	25	89	0	0	0
11	76	25	89	0	0	0
12	76	25	89	0	0	0
13	76	25	89	0	0	0
14	76	25	89	0	0	0
15	33	25	89	-1.628	0	0
16	119	25	89	1.628	0	0
17	76	4	89	0	-1.628	0
18	76	47	89	0	1.638	0
19	76	25	89	0	0	-1.628
20	76	25	89	0	0	1.628

Extensive pretesting

The extensive pretesting was done to better understand the behavior of the boiler system and to determine the best operating conditions for higher boiler efficiency (BEFF). Three independent variables were primary air damper (PAD) opening, secondary air damper (SAD) opening, and depth of fuel bed (DFB). The range of these input variables were as follows:

PAD = 0 to 250 mm

SAD = 0 to 60 mm

DFB = 0 to 150 mm

The McNay wood fired-boiler was operated in the beginning with PAD opening of 25 mm, SAD opening of 50 mm and DFB of 40 mm. A 3^3 factorial experimental design was utilized to estimate the relationship between BEFF and the set of independent variables. During extensive pretesting, the general vicinity of the optimum conditions were determined as given below:

PAD = 76 mm

SAD = 25 mm

DFB = 89 mm

After finding the region of the optimum boiler performance, a quadratic central composite design was employed to locate the optimum.

The grate burner has three positions, two extreme position are for cleaning purposes and the middle position provided best combustion of the fuel. Grate position was kept constant during the entire period of boiler operation (Fig. 38). Ash was removed almost twice a week (Fig. 39). Flue and boiler base were cleaned after every 2 to 4 weeks (Figs. 40 & 41).

Performance testing

Twenty performance tests were taken as required by the central composite design of the experiment for this research. All these tests were randomly taken while the boiler was operating in on-cycle mode (PAD open and induced draft (I.D.) fan On) under steady state conditions. In fact, the boiler was operated under partial load conditions, and three modes of operation were observed, which are as follows:

Partial-Cycle	:	PAD closed and I. D. fan on
On-Cycle	:	PAD open and I. D. fan on
OFF-Cycle	:	PAD closed and I. D. fan off

During these tests, the boiler room conditions were almost constant with room air temperature of 21°C and relative humidity of 25%. The inclined grates of the burner were cleaned before starting each test and data were not taken until the flue gas temperature became constant. The duration of these tests could not be more than

Figure 38. Inclined grates of the burner

Figure 39. Ash pit door and wood fuel ash

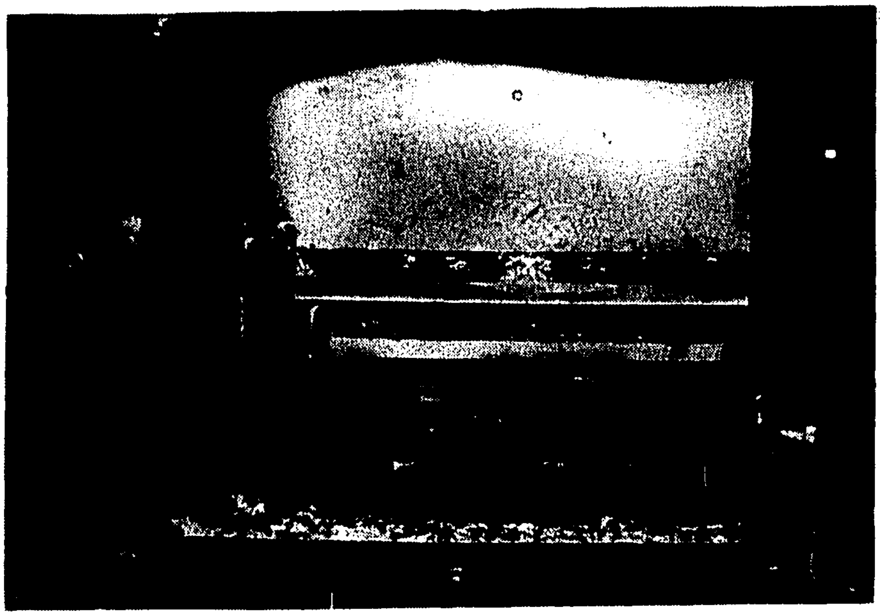


Figure 40. Removal of ash and cleaning of boiler base

Figure 41. Boiler flue opened for cleaning

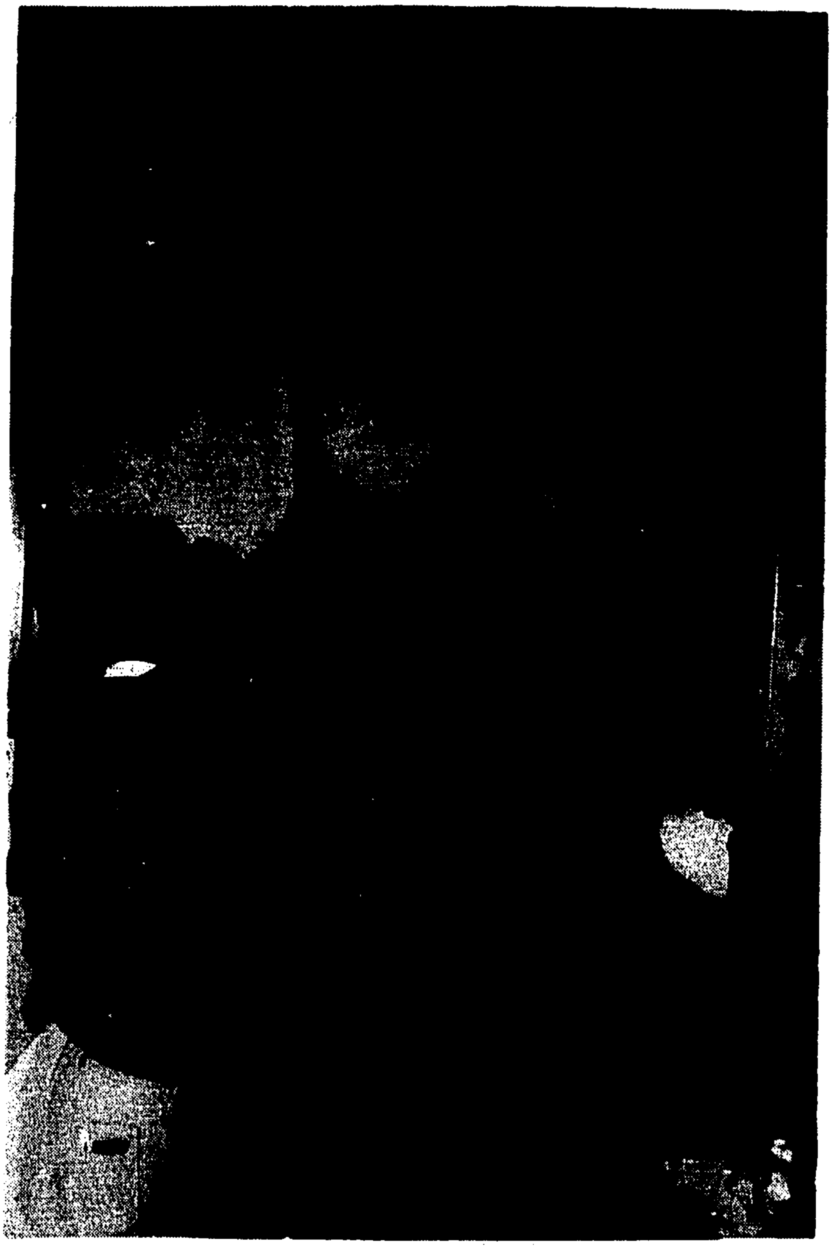
an hour due to the limitation of energy demand from the system. The fuel feed could not be accurately measured for each performance test and heat loss method was used in boiler efficiency calculations. The flue gas analysis was made every 3-5 minutes after constant readings for percent CO_2, O_2, and CO were obtained under steady state conditions for each test or set of operating conditions. The data for flue gas analysis, flue gas temperature, and flue gas mass flow were collected at the same time and from exactly the same location in the flue gas duct (Fig. 42).

In addition to temperature measurements by thermocouples at various points in the boiler system, display type thermometers were also installed to check accuracy and for demonstration purposes. Besides data collection and recording by data logging system, a test data form and check list were developed and used to manually record data and other important information about the test.

Extended period testing

The extended period tests were taken after completion of performance tests and after permanently incorporating those optimum determined operating settings of PAD, SAD and DFB for maximum boiler performance. The boiler was operated in all three cycle modes. The duration of extended period testing was 3-4 hrs. The inclined grates were always cleaned before starting the extended period tests. The

Figure 42. Flue gas temperature, flue analysis and flue gas velocity measurements from the same location of the boiler rectangular duct



boiler efficiency and other performance parameters such as fuel feed rate, flue gas temperature, unburned carbon, etc., were measured in all three modes of operations at various indoor temperature and humidity conditions.

Continuous monitoring

The boiler performance was continuously monitored while operating at the optimum settings during the winter season. The grates of the burner were cleaned at least twice a day. From the continuous monitoring data, the seasonal efficiency of the boiler system, total wood-chips consumed, and total thermal energy delivered to the house and shop were determined.

RESULTS AND ANALYSIS

The results and analysis of wood-fired boiler energy system are presented in five parts:

1. wood chip fuel analysis
2. boiler thermal and emission performance analysis
3. energy analysis
4. economic analysis
5. operating experience with integrated system

Wood Chip Fuel Analysis

Whole tree wood chips from hardwood species such as elm, maple, oak, and hickory from natural forest wood resources on the McNay farm were burned in the boiler system. The average moisture content of green whole tree wood chips was found to be 45%. The average bulk density of green wood chips was about 300 kg/m^3 (18.7 lb/ft^3).

The fuel proximate and ultimate analyses are listed in Table 6. The higher heating value for wood chip fuel used in the McNay boiler energy system is estimated at 19.75 MJ/kg on dry basis. During the whole winter season, the boiler system burned wood fuel having almost constant physical and chemical characteristics, because the variation due to wood species, age of tree, moisture content were kept to a minimum throughout the heating season.

Table 6. Wood fuel analysis

<u>Fuel characteristics</u>

Species: elm, maple, hickory and oak

Fuel type: whole tree green wood chips

Average density: 300 kg/m^3 (18.70 lb/ft^3)

	Percent	
	As-received	Oven dry bases
Proximate analysis		
Moisture	45.0	0.0
Volatile matter	46.66	84.85
Fixed carbon	7.60	13.80
Ash	0.74	1.35
Ultimate analysis		
Moisture	45.0	0.0
Carbon	27.85	50.64
Hydrogen	3.31	6.02
Oxygen	22.96	41.74
Nitrogen	0.14	0.25
Sulfur	0.0	0.0
Ash	0.74	1.35
HHV, MJ/kg	10.86	19.75

Boiler Thermal and Emission Performance Analyses

The boiler thermal and emission performance analyses are presented with special reference to boiler testing and its monitoring during the winter heating season of 1989-90, as follows:

1. performance test analysis
2. extended period test analysis
3. continuous monitoring analysis
4. effect of operating variables on boiler performance

Performance test analysis

The effects of three independent parameters, primary air damper (PAD), secondary air damper (SAD), and depth of fuel bed (DFB) on the wood-fired boiler system performance and efficiency were experimentally measured and analyzed. The quadratic central composite design was used to collect performance test data. A total of 20 performance tests were randomly conducted under steady state conditions of the boiler operation. The PAD opening was varied from 51 mm to 119 mm, SAD opening was varied from 4 mm to 47 mm and DFB was varied from 46 mm to 132 mm. Table B-1 in Appendix B shows the values of these variables for each test, and the corresponding measured boiler system efficiency. The boiler efficiency was calculated by using heat loss method (equation 11), and an example of the calculation for a performance test is also given in Appendix B.

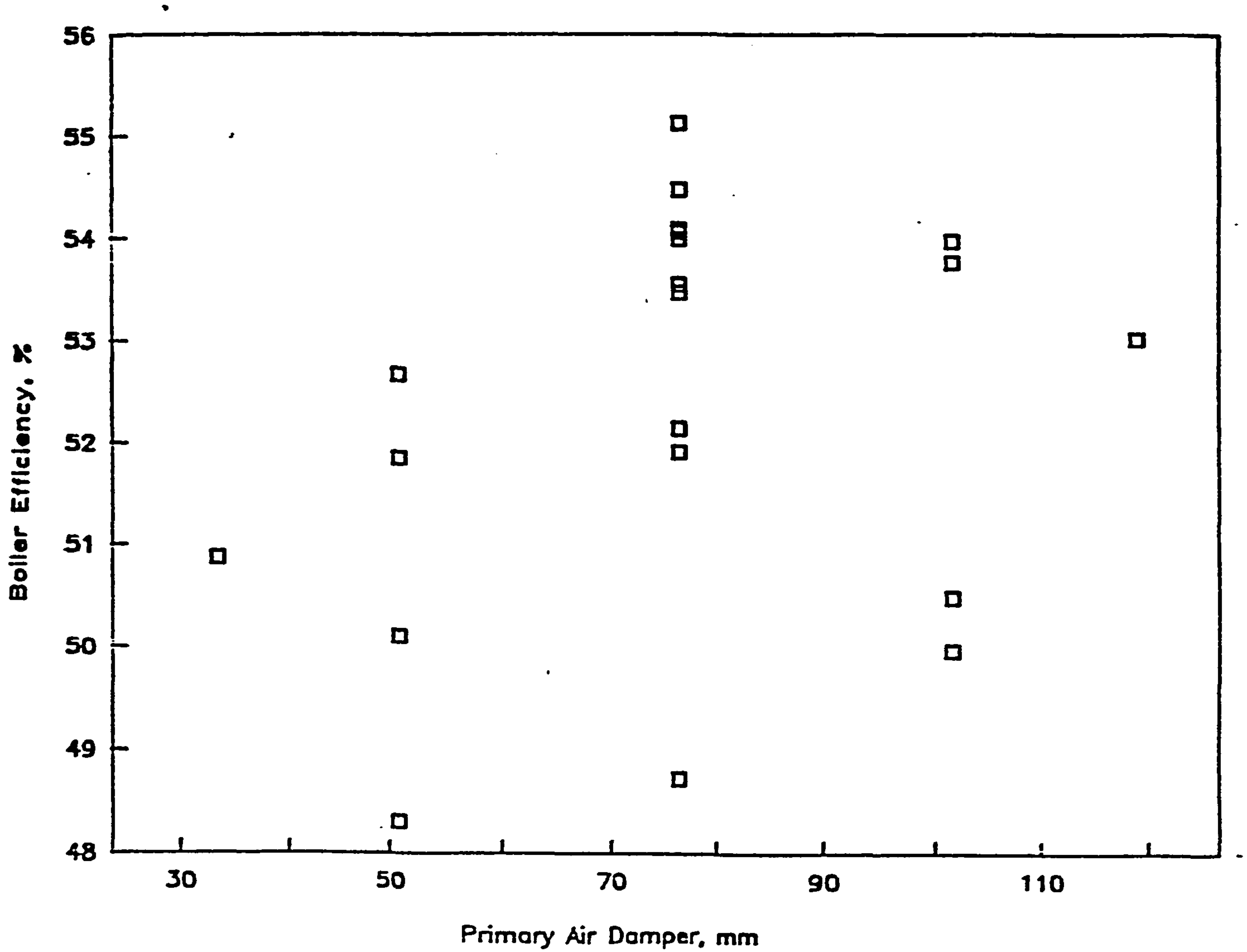


Figure 43. Relationship between primary air damper opening and boiler efficiency

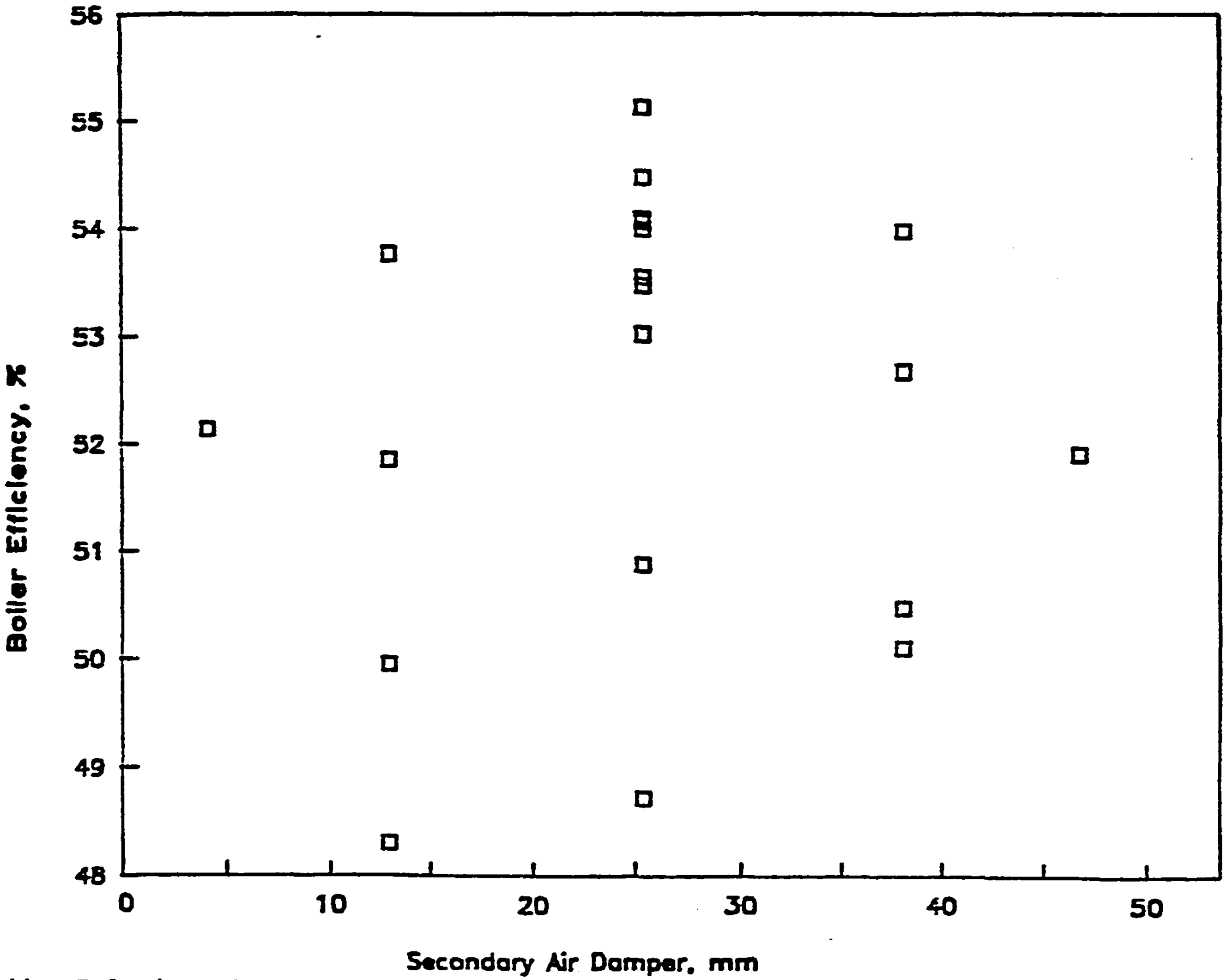


Figure 44. Relationship between secondary air damper opening and boiler efficiency

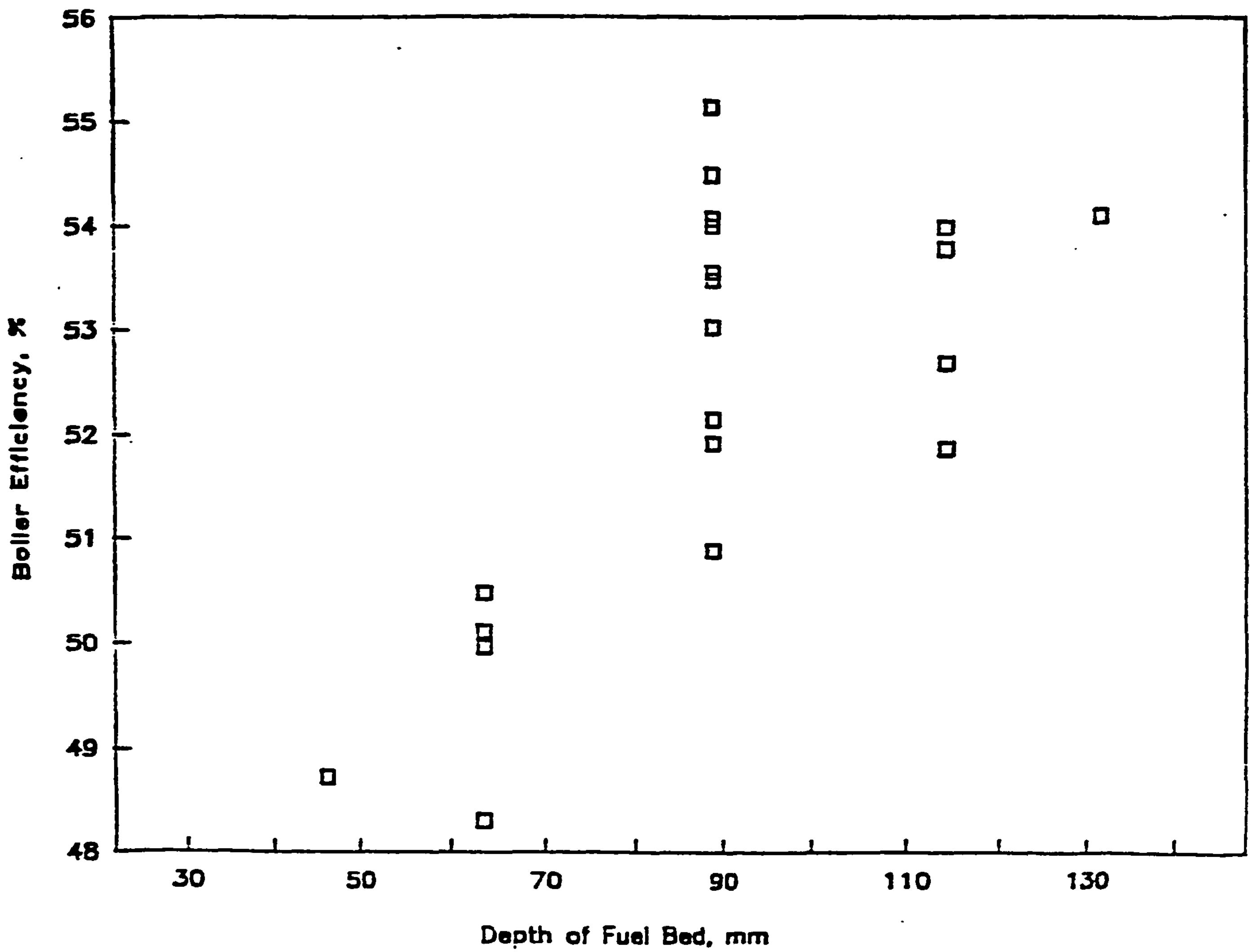
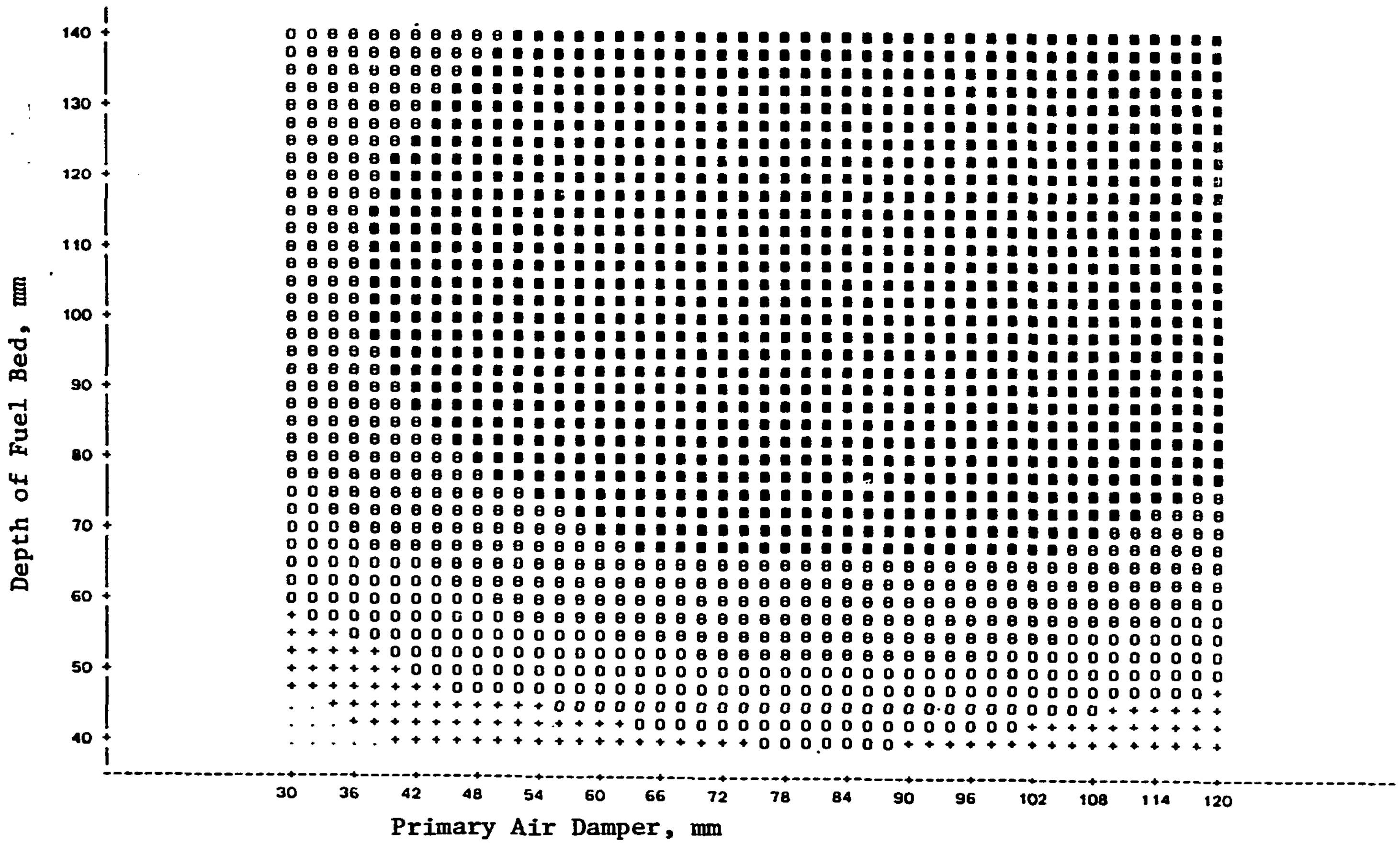


Figure 45. Relationship between depth of fuel bed and boiler efficiency

Figs. 43, 44, and 45 illustrate the relationship between input variables PAD, SAD, and DFB with boiler system efficiency respectively. It can be observed from these figures that the relationships between operating variables and boiler efficiency are not linear but are strongly quadratic.

The complete statistical analysis is given in Appendix C. The analysis of variance indicates that the model (regression) is highly significant, and lack of fit is not significant; which shows that the quadratic central composite design is an adequate approximation for this experiment. The primary air damper and depth of fuel bed have greater effect on the boiler efficiency than does the secondary air damper. Fig. 46 shows the contours of boiler efficiency as a function of primary air damper and depth of fuel bed while secondary air damper is kept constant at 25 mm. The interactions between these operating conditions were found to be not significant, which indicates that the input variables for operating conditions act independently of each other. The quadratic effect of all three input variables have significant effect on boiler system efficiency. Thus the analysis of data to measure the interrelationship of PAD, SAD, and DFB on the wood-fired boiler efficiency illustrates that the boiler system efficiency can be described by a quadratic function of these input operating variables. The equation for this relationship is as follows:



SYMBOL	Y	SYMBOL	Y	SYMBOL	Y
......	43.81408 - 44.92923	000000	47.15952 - 49.38980	■■■■■■	51.62009 - 53.85038
++++++	44.92923 - 47.15952	888888	49.38980 - 51.62009	■■■■■■	53.85038 - 54.96552

Figure 46. Contour of a boiler efficiency as a function of primary air damper and depth of fuel bed while secondary air damper is kept constant (25.4mm)

$$BEFF = 21.996 + 0.2169\ PAD + 0.3686\ SAD + 0.3399\ DFB - 0.001269\ PAD^2 - 0.0049235\ SAD^2 - 0.001574\ DFB^2 - 0.0007379\ PAD * SAD + 0.00023056\ PAD * DFB - 0.000503\ SAD * DFB \quad (32)$$

The optimum operating conditions experimentally determined were as follows:

Primary air damper (PAD) = 76 mm

Secondary air damper (SAD) = 25 mm

Depth of fuel bed (DFB) = 89 mm

At these optimum operating conditions, the boiler system efficiency was measured to be 54% while burning green wood chips at 45% moisture content on wet basis. The amount of excess air was found to be 39.0% and the fuel consumption rate was measured at 40 kg/h. Similarly, the carbon dioxide concentration in the flue gas was about 14% (Table 7). The fuel energy input was measured at 434.6 MJ/h and 234.6 MJ/h of functional thermal energy was delivered for space heating. Fig. 47 illustrates the heat energy balance for the boiler system under optimum operating conditions. It was determined that total stack heat loss was about 38.4% of fuel input energy and heat loss due to unburned carbon (ash) was 2.6%.

The optimum operating conditions or optimum setting of primary air damper, secondary air damper and depth of fuel bed remained

Table 7. Optimum operating conditions and boiler system performance under steady state conditions

Thermal conditions		
Boiler room temperature	=	21 degree C
Boiler room relative humidity	=	25 %
Wood chip fuel moisture	=	45 % (on wet basis)
Optimum operating conditions		
Primary air damper (PAD)	=	76 mm
Secondary air damper (SAD)	=	25 mm
Depth of fuel bed (DFB)	=	89 mm
Boiler performance		
Boiler system efficiency	=	54.0 %
Excess combustion air	=	39.0 %
Fuel consumption rate	=	40.0 kg/h
Flue gas temperature	=	371 degree C
Carbon dioxide	=	14.0 %
Carbon monoxide	=	0.0 %
Oxygen	=	6.5 %
Nitrogen	=	79.5 %
Fuel input energy	=	434.6 MJ/h
Boiler functional energy	=	234.6 MJ/h

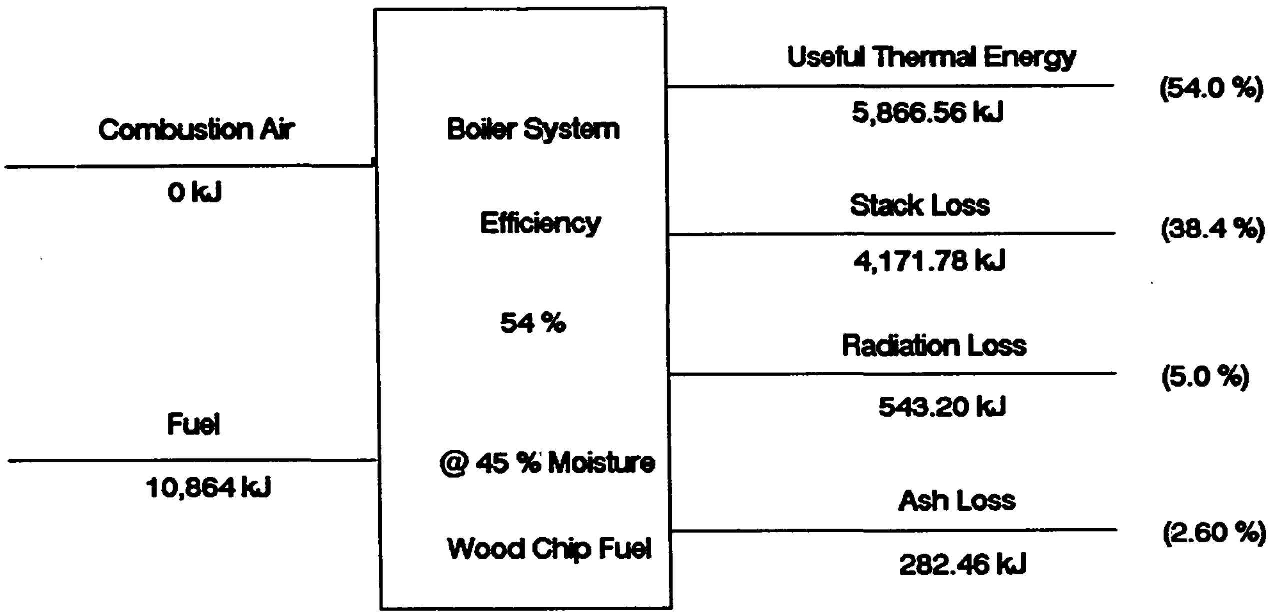


Figure 47. Energy balance for boiler system under optimum-cycle operation

constant for boiler operation during the winter season as well as during extended period testing and monitoring.

Extended period test analysis

It was found during testing that the wood-fired boiler system has a relatively large capacity compared to the average energy load on the system. Due to the infeasibility of increasing the system load, the boiler was operated at part load conditions during the winter heating season. It was observed that the boiler system was operating in three cycle modes. The first mode is called partial-mode or partial-cycle, when the primary air damper is closed and the induced draft fan is on. The second mode of operation is called optimum-mode or on-cycle when the primary air damper is open and the induced draft fan is on. The third mode of operation is called off-mode or off-cycle when the primary air damper is closed and the induced draft fan is off.

The most desirable mode of boiler operation is optimum-cycle mode when boiler efficiency or performance is maximum, which was determined at 54% during the boiler performance tests. Boiler operation for an extended period in the other two modes of operation is undesirable with respect to boiler performance. In the case of petroleum and natural gas heating systems, when the working fluid attains its preset conditions or maximum temperature, the main burner and fuel supply shuts off immediately, but in the case of a wood-fired system after achieving the desired thermal conditions the supply of wood on the grate continues to keep the fire on. The boiler efficiency was measured in all three modes of operation, when boiler room air temperature was about 21 degree C and relative humidity was in the range of 25%. During partial-mode operation, the boiler system efficiency was determined to be about 36%. Similarly, the boiler efficiency in off-cycle mode was found to be about 28% (Table 8). Fig. 48 and 49 show the heat energy balance for both partial and off-cycle operation of boiler under steady state conditions. It can be noted that about 55.1% and 62.8% of the total fuel energy input was lost as stack heat losses in partial and off-cycle operation respectively. The fuel consumption during partial cycle and off-cycle operation was measured at about 25 kg/h and 13 kg/h respectively. The relationships among fuel consumption rate, carbon dioxide concentration in flue gas and boiler system efficiency in three modes of boiler operations are illustrated in Fig. 50. All these three performance parameters are significantly higher at optimum-cycle operation of the boiler system.

As indicated in Table 8, it was observed that during partial and off-cycle conditions, the percent excess air increased drastically in the flue gas. The concentration of carbon dioxide during partial and off-cycle modes of boiler operation reduced to 4.25% and 2.60%

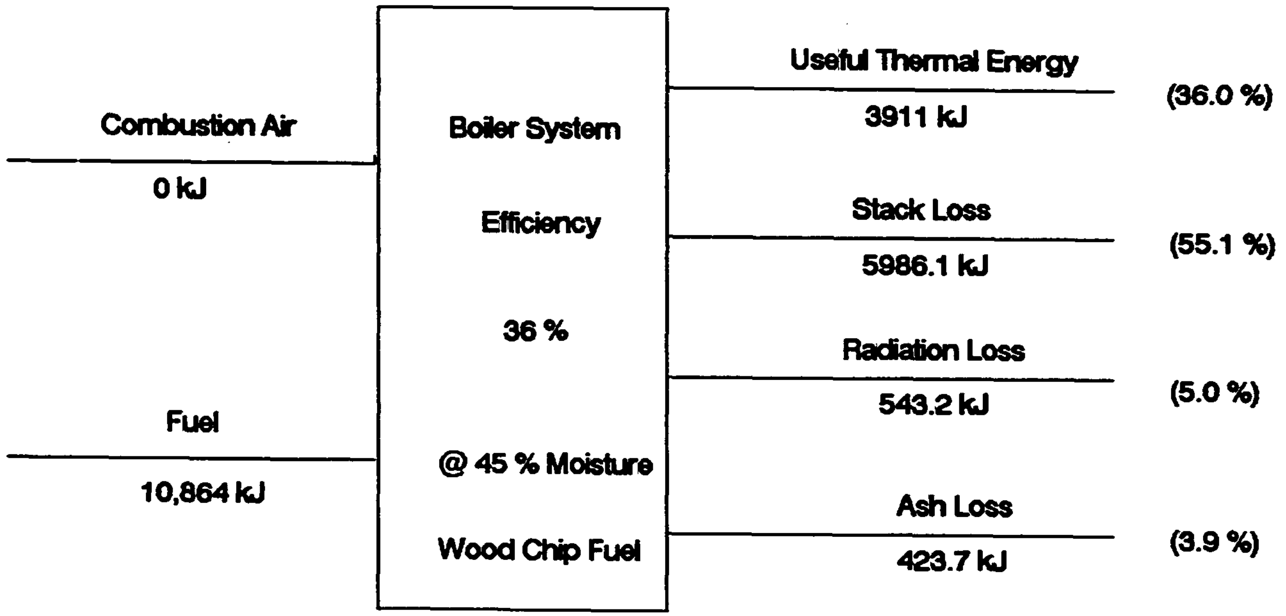


Figure 48. Energy balance for boiler system under partial-cycle operation

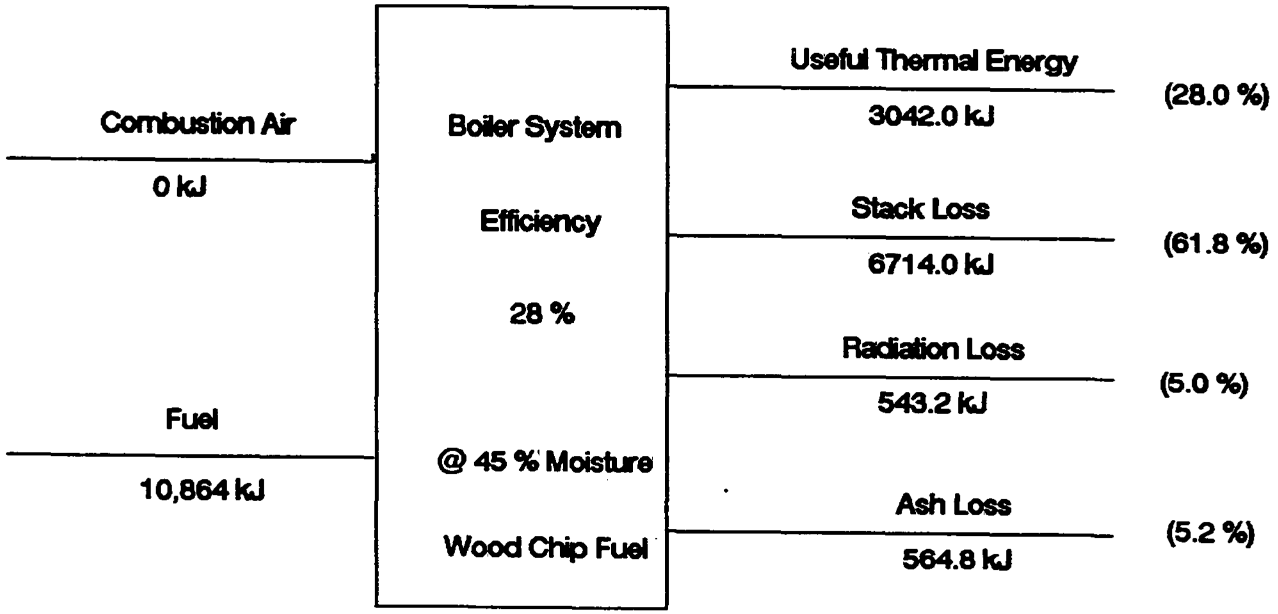


Figure 49. Energy balance for boiler system under off-cycle operation

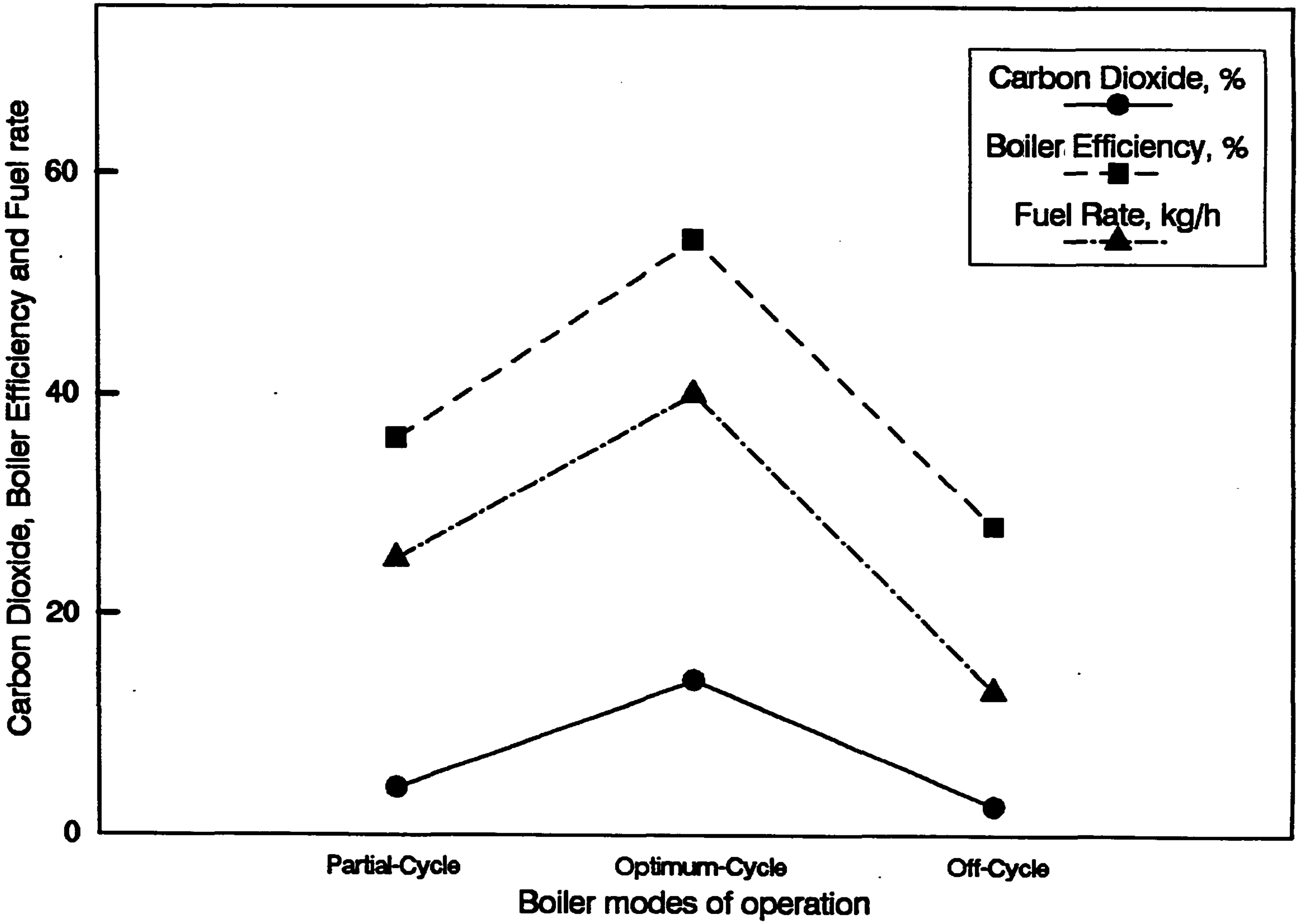


Figure 50. Relationship between boiler efficiency and carbon dioxide concentration in three modes of boiler operation

Table 8. Operating cycles and boiler performance under steady state conditions

	Operating cycles 1 Partial-cycle	2 Optimum-cycle	3 Off-cycle
Operating Conditions			
Primary air damper	Closed	Open	Closed
Induced draft fan	On	On	Off
Boiler performance			
System efficiency, %	36	54	28
Fuel Consumption, kg/h	25	40	13
Flue gas temperature, degree C	260	371	204
Carbon dioxide, %	4.2	1.4	2.6
Excess air, %	351	39	624
Unburned carbon, %	4.5	3.0	6.0

respectively. Actually, in these modes of operation, when the primary air damper was closed, the firing rate or rate of combustion was reduced and more air entered through the secondary air damper.

It was also noted during extended period testing that the boiler system was operating for less time in the optimum-cycle mode as compared to partial and off-cycle conditions. Table 9 illustrates results of 18 extended period tests of 3-4 hours duration at different room air thermal conditions the while boiler was operating normally in all three modes of operations. The boiler efficiency varied from 29 to 40% depending upon the energy load and combustion air temperature. The boiler efficiency was calculated by using input-output method (equation 10), and an example of the calculation for a extended period is given in Appendix B.

Continuous monitoring analysis

The boiler was test fired in late November, 1989. The operation of the wood-fired boiler was again started in the first week of December, 1989. The continuous monitoring and recording of thermal energy data using the computer acquisition system started on December 16, 1989, when in addition to the house, the workshop was also connected to the boiler system for space heating. The boiler system operation was monitored for about 3 1/2 months (14 weeks) from December 16, 1989 to March 31, 1990. Table 10 lists some monitoring data, including total fuel consumed and seasonal thermal energy delivered to the house and the workshop in each month and during the winter season of 1989-90. The total thermal energy delivered to the house and shop was measured to be 60,836 kwh or 219,010 MJ. Of this, about two-third of the energy was delivered to the house and one-third was delivered to the workshop.

Table 10 also indicates that during the last 2 weeks of December 1989, the highest seasonal boiler efficiency of 37% was measured. For the month of January, 1990, seasonal efficiency was about 33.0%, and about 32% was for the month of February, 1990. The month of December, 1989 was comparatively much colder (average ambient temperatures are given in Table 10) than the rest of the winter months. Due to this cold weather, the thermal energy load on the boiler system increased and resulted in a higher seasonal efficiency of the boiler system. Figs. 51a, b, and c show the seasonal energy load, fuel consumed, and seasonal boiler efficiency during the winter season from December 16, 1989 to March 31, 1990.

Effect of operating variables on boiler performance

The major operating variables which affect the performance of the McNay wood-fired boiler energy system are listed below:

1. wood fuel quality
2. combustion air quality

Table 9. Extended period boiler system test results at different room air thermal conditions

Boiler room air Temperature °C	Fuel consumed kg/h	Heating load kw	Heating load MJ/h	Boiler system efficiency %
26.2	21.2	19.5	70.4	30.5
26.2	21.3	21.2	76.5	30.2
23.7	26.5	23.2	84.3	29.2
23.7	25.0	24.4	87.7	32.3
21.2	28.3	25.7	92.5	30.1
21.2	24.2	26.2	94.7	36.0
21.2	26.2	27.0	97.0	34.0
21.2	27.0	27.2	97.8	33.3
18.7	26.3	29.3	105.5	37.0
18.7	28.1	30.2	108.9	35.7
15.2	29.9	31.0	111.5	34.3
15.2	29.6	32.9	118.3	36.8
12.7	29.0	34.3	123.4	39.2
12.7	32.7	34.5	124.1	35.0
12.7	30.5	34.7	125.1	37.7
12.7	33.0	35.3	127.0	35.5
10.2	31.7	37.1	133.5	38.8
10.2	32.7	38.5	138.7	40.5

Table 10. Seasonal boiler system performance and wood fuel consumption during winter season 1989-1990

	Winter Heating Months[a]				
	December	January	February	March	Total
Average ambient temperature, °C	- 9	- 0.2	0.1	5.7	
Wood fuel[b] consumed, kg	11,878	18,811	16,341	13,457	60,487
Energy delivered to house[c],					
kwh	9,382	12,960	9,842	8,396	40,580
GJ	33.775	66.656	35.431	30.226	146.088
Energy Delivered to workshop,					
kwh	3,840	5,752	5,951	4,713*	20,256
GJ	13.824	20.707	21.424	16.967	79.922
Total farmstead energy delivered,					
kwh	13,222	18,712	15,793	13,109	60,836
GJ	47.599	67.363	56.855	47.192	219.009
Boiler seasonal efficiency, %	37	33	32	31	33.3

[a]Wood-fired boiler system operated from December 16, 1989 to March 31, 1990.

[b]Whole tree green wood chips at 45% moisture on a wet basis.

[c]Average house temperature was maintained at 19.5°C during December 1989, and 21.5°C during January and February, and 22.5°C during March 1990.

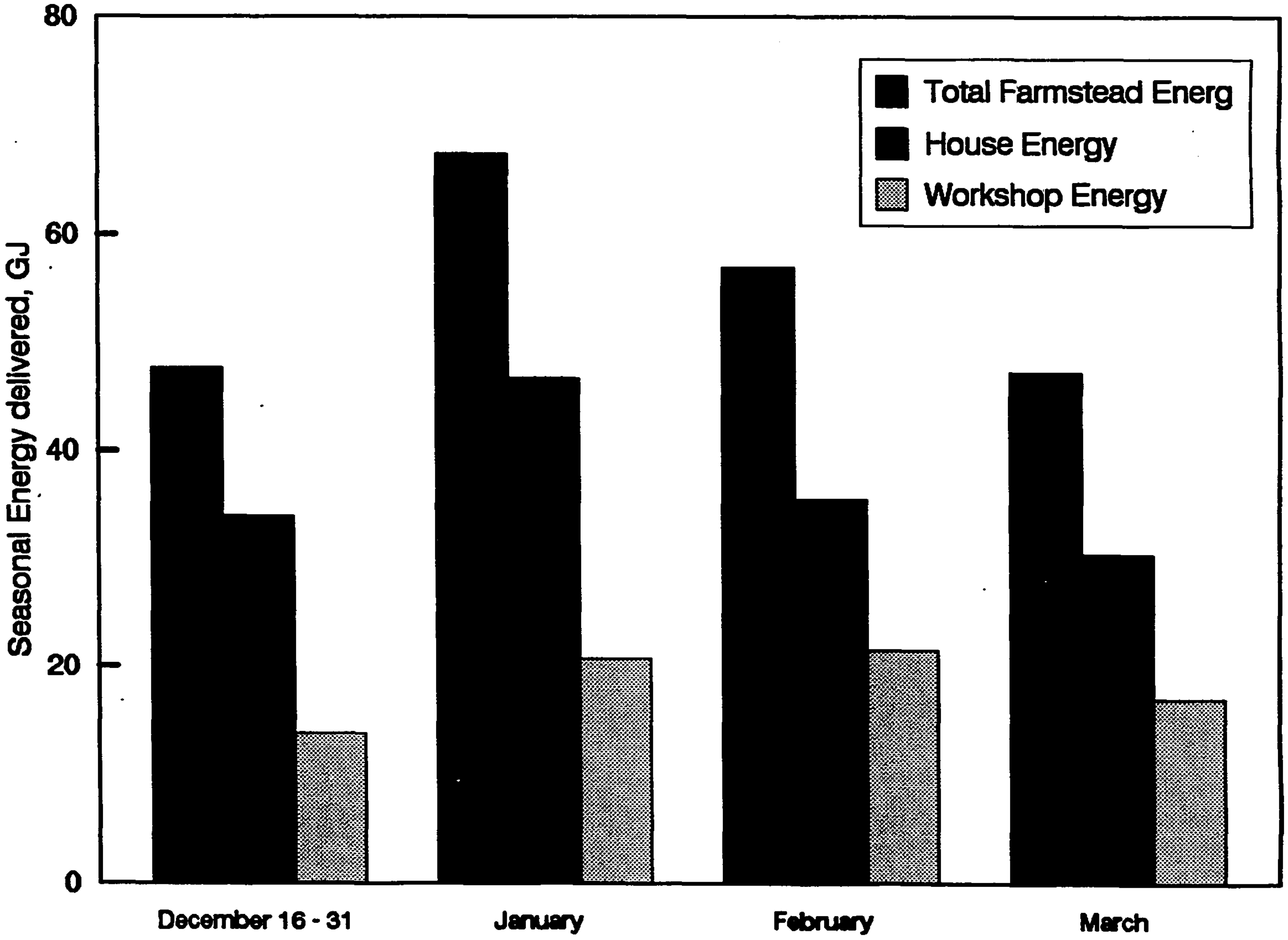


Figure 51a. Seasonal energy delivered for farmstead applications during the winter heating season from December 16-31, 1989 to March, 1990

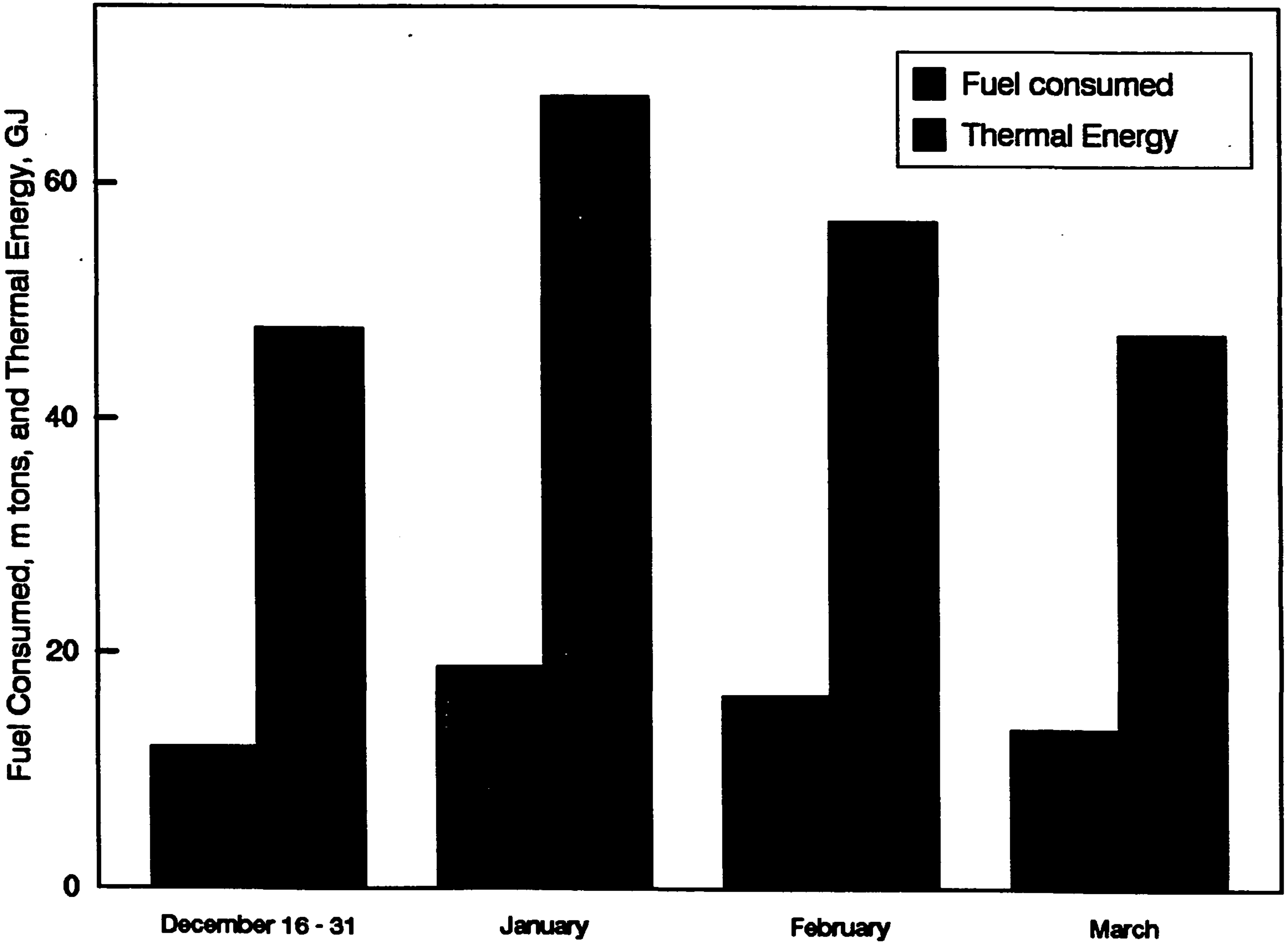


Figure 51b. Seasonal wood fuel consumption and energy production

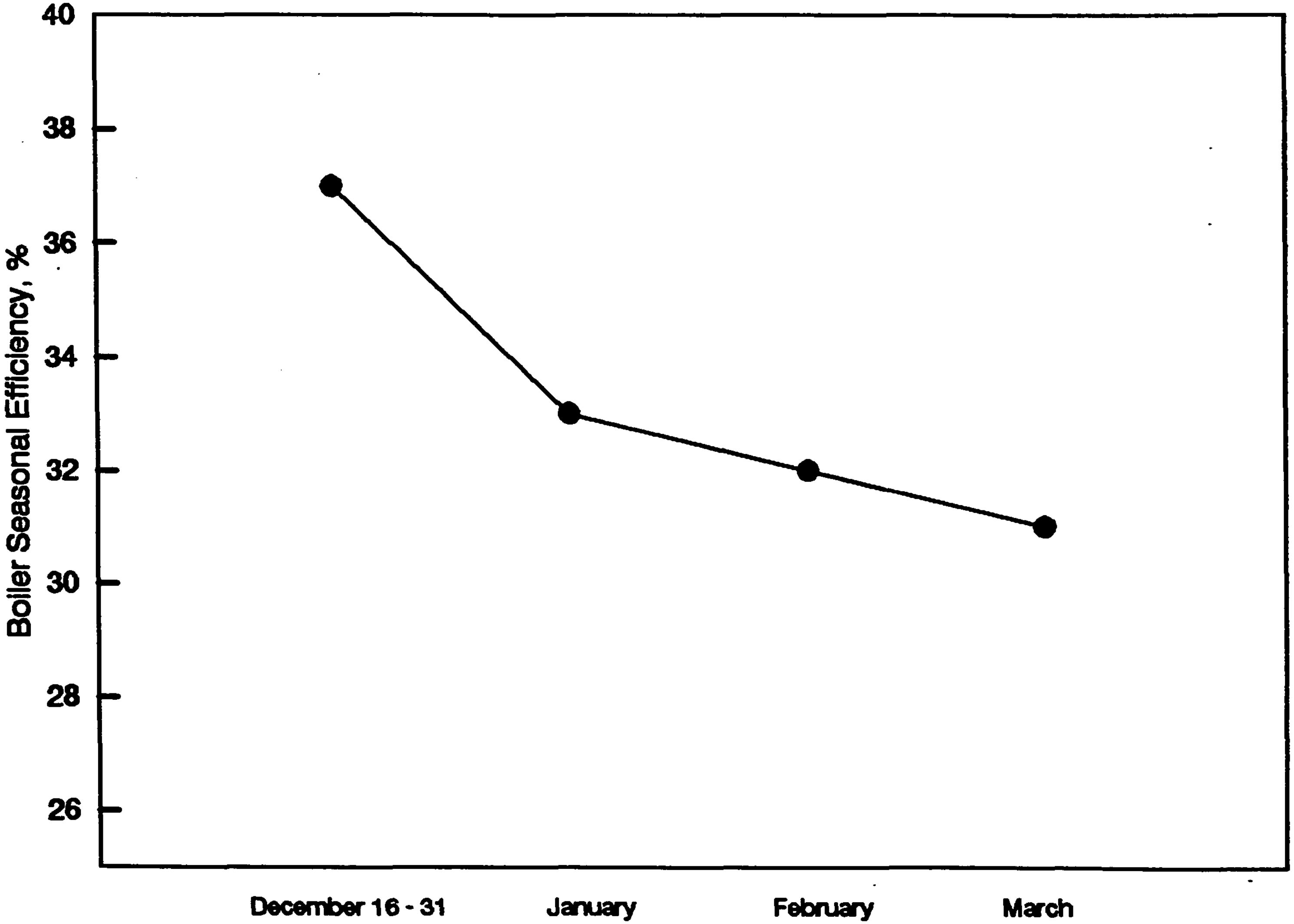


Figure 51c. Seasonal boiler efficiency

3. flue gas temperature

4. amount of excess air

5. boiler feed water and hot water temperature

6. boiler system energy load

Wood fuel quality The wood chip fuel affects boiler efficiency primarily due to fuel moisture content, which increased the latent heat losses caused by vaporization of water in the fuel and water formed by combustion of hydrogen. The fuel carbon contents and hydrogen/carbon (H/C) ratio mostly remain unchanged in case of wood fuels. Fig. 52 shows the relationship of fuel moisture to stack loss and boiler efficiency of the wood-fired boiler system under steady state conditions. In addition to boiler efficiency, the fuel quality (wood fuel moisture and density) greatly affects the design and capacity of the fuel handling and storage system.

Combustion air quality Combustion air quality primarily includes air density and air temperature, which affect the boiler efficiency due to presence of water vapor (humidity) and heat content of incoming combustion air. Combustion air density is inversely proportional to water vapor content and air temperature. When water vapor increases, the air density decreases, and when temperature rises, the air expands and the number of air molecules in a given volume is reduced. The boiler efficiency can be increased or boiler system losses can be reduced by preheating combustion air. Fig. 53

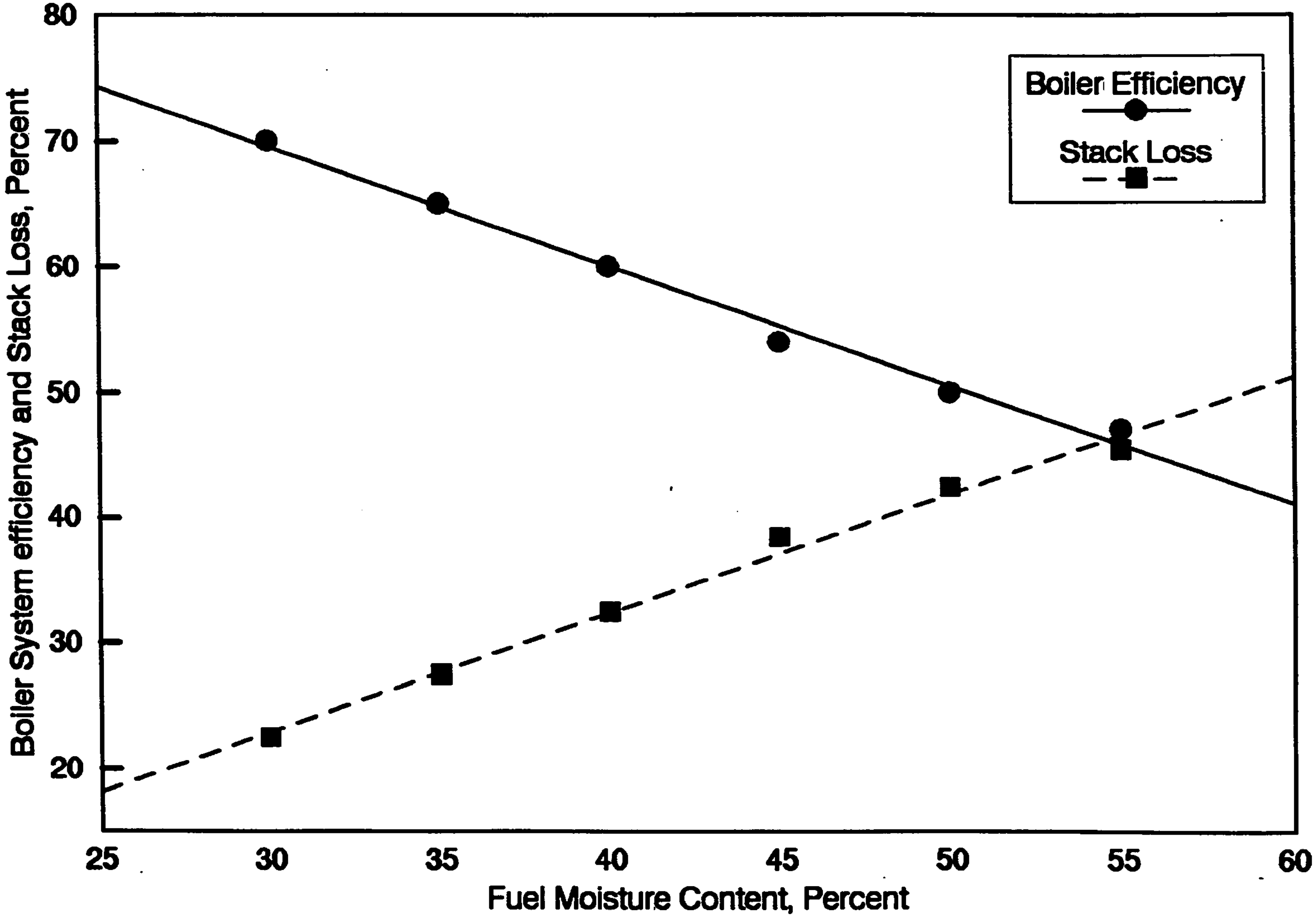


Figure 52. Effect of wood fuel moisture content on boiler system efficiency and stack losses

shows the relationship between combustion air temperature and boiler efficiency for the McNay wood-fired boiler. The efficiency of the boiler drops as combustion air temperature increases. The increase in boiler efficiency at lower temperature is due to the increase in energy load on the system.

Flue gas temperature Flue gas temperature is the single most important indicator of performance of a wood-fired boiler system. Lower flue gas temperature with higher percent carbon dioxide in flue gas increases efficiency and results in lower stack heat loss. Conversely, higher flue gas temperature with lower percent of carbon dioxide lowers the boiler efficiency and results in more heat loss to stack. Both quality and quantity of fuel and combustion air affect the flue gas temperature. The amount of excess air influences the flue gas temperature and carbon dioxide concentration in the flue gas. The rate of heat transfer to the working fluid, heat transfer surface area and heat transfer time affect the flue gas temperature. Boiler fireside and waterside scaling or sooting also influence the flue gas temperature. For the McNay wood-fired boiler system, flue gas analysis indicated that carbon dioxide percentage in the flue gas increases with increase in flue gas temperature and results in a higher efficiency. Fig. 54 demonstrates the relationship between flue gas temperature and the wood-fired boiler efficiency and flue gas carbon dioxide content under steady state conditions.

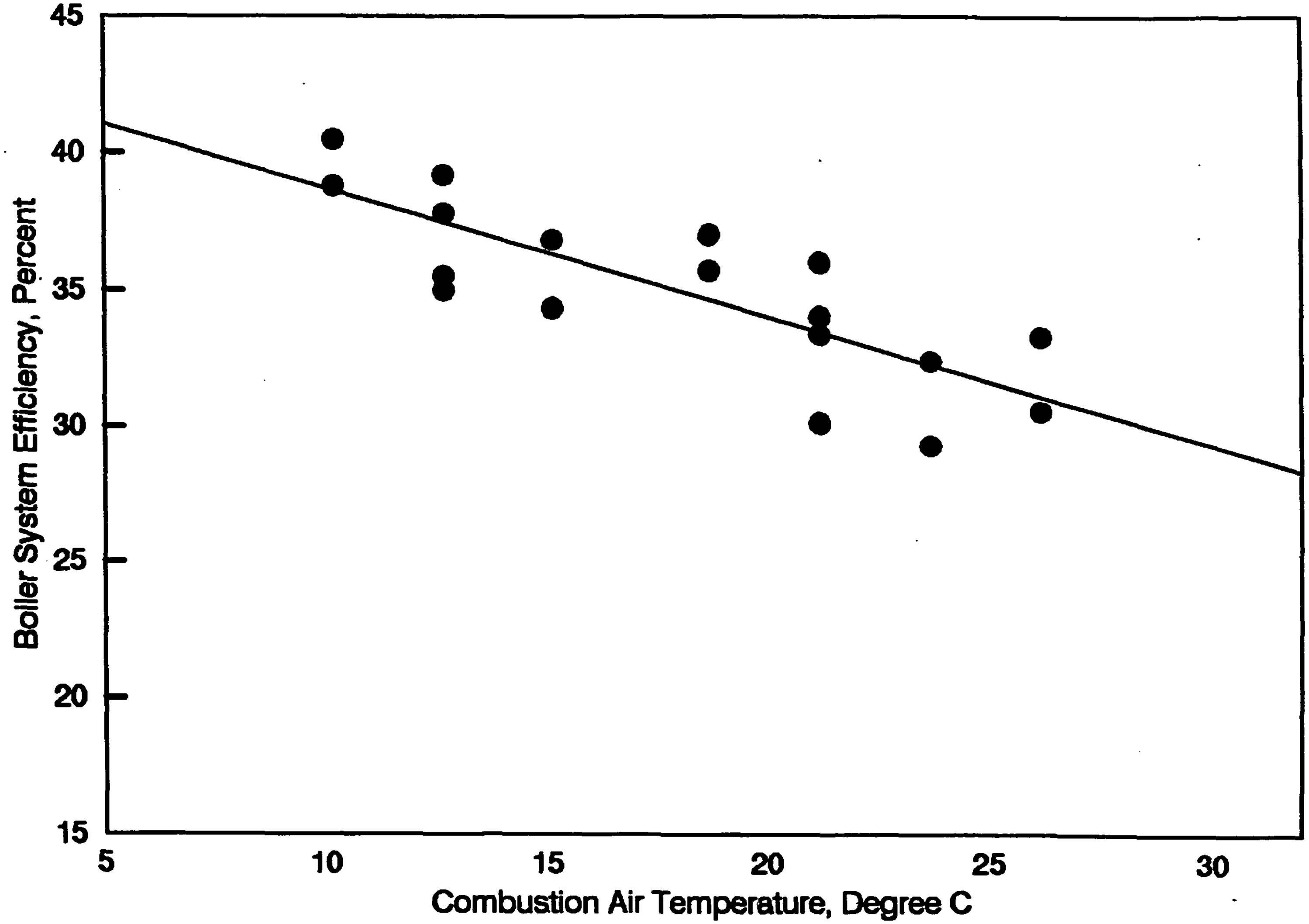


Figure 53. Effect of combustion air temperature on boiler system efficiency

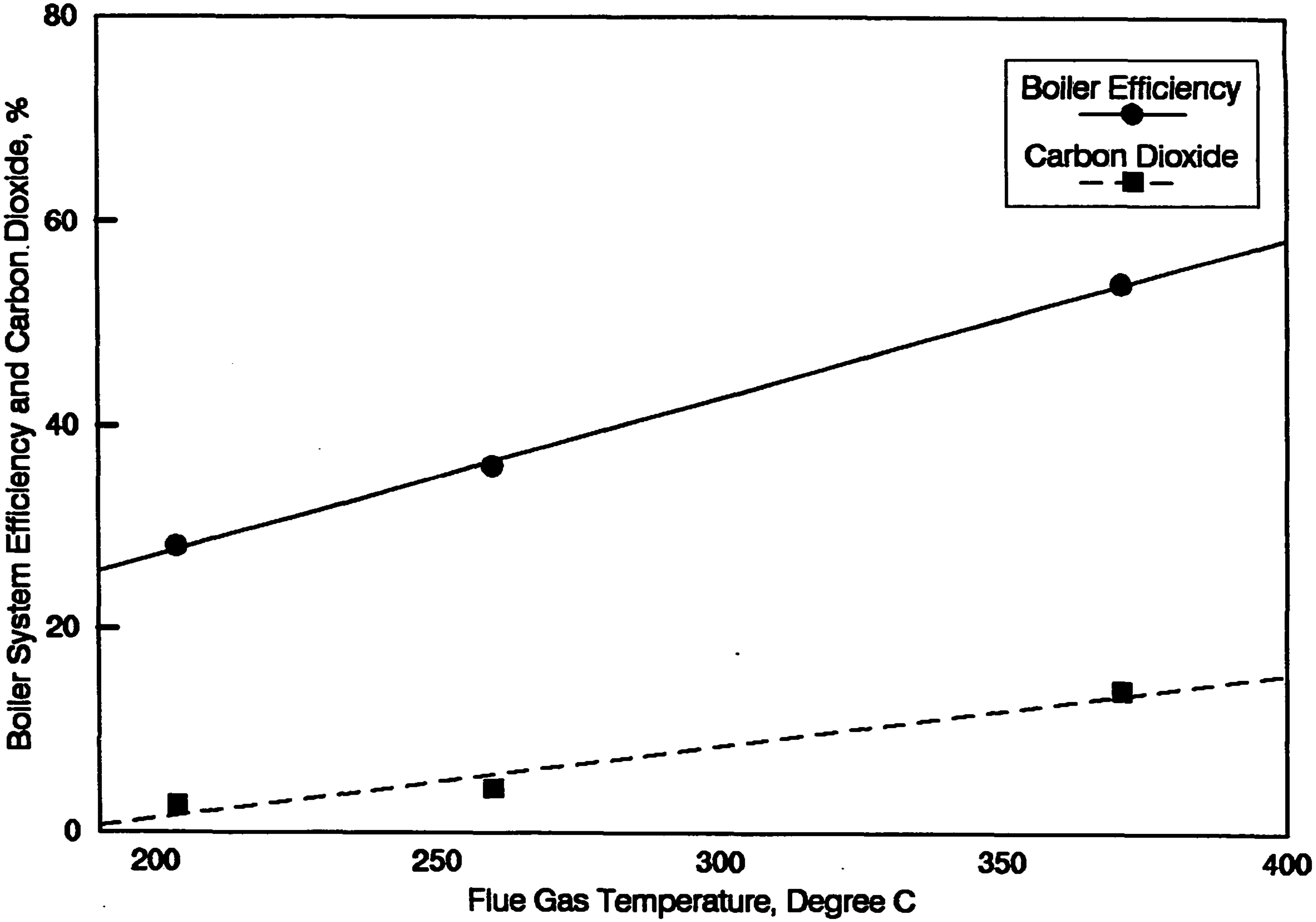


Figure 54. Relationship between flue gas temperature, carbon dioxide and system efficiency

<u>Amount of excess air</u> The amount of excess air affects the mass flow rate and temperature of the flue gas. It was determined for the McNay wood-fired boiler, that the efficiency is maximum when excess air is about 39%. Thus, the right amount of excess air increases the boiler efficiency and ensures complete combustion.

<u>Boiler feedwater and hot water temperature</u> It was found that the boiler efficiency was greatly affected by the outgoing hot water temperature and incoming feedwater temperature. The high flue gas temperature observed with the McNay boiler system, can be used to preheat the boiler feed water to improve efficiency even under full load conditions, and the boiler system would deliver more heat even during peak energy loads. Thus boiler efficiency can be increased by increasing the temperature of boiler feedwater by adding a flue gas waste heat recovery surface called an economizer. The economizer can absorb heat from high temperature flue gas and preheat relatively cold feed water. Similarly heat transfer to the hot water can be increased by improving the waterside heat transfer surface of the boiler system.

<u>Boiler system energy load</u> The boiler load can be expressed in percent of its maximum capacity. The load on a boiler system affects its efficiency and overall performance in number of ways.

The heat loss due to radiation to the surroundings for the McNay wood-fired boiler system or any boiler system is very much constant regardless of percent boiler load. When the boiler system is operating in under-load or partial load conditions, the firing rate goes down and radiation loss, which is essentially constant becomes a larger percentage of the fuel energy input. For example, 5% radiation loss for the McNay wood-fired system at full energy load or 100 percent system capacity becomes 10% at 50 percent system load capacity and 20% at 25 percent system load capacity.

For a gas or oil fired boiler system, the combustion process completely ends when energy is not needed. But for a wood-fired system, the combustion process remains continuous at some lower rate even after achieving the desired energy conditions. When the system is operating at partial load conditions, it attains its preset temperature for hot water delivery in comparatively less time and the primary air damper closes, which reduces the draft in the combustion chamber. The induced draft fan is also switched off. Under these conditions, the combustion rate slows down, resulting in a greater unburned carbon loss. This unburned carbon can block the openings in the grates and ash passage and cause the fuel flowability problems. Additional air from the secondary air damper cools the fuel and reduces distillation and combustion of the volatiles. This reduces the temperature of combustion gases and increases the percentage of oxygen in the flue gas flow. The low gas temperature reduces the rate of heat transfer to boiler working fluid and lowers the boiler performance.

In this situation, when temperature of the boiler outgoing water further drops, the boiler system control opens the primary air damper to increase the rate of combustion. This increases the furnace draft and the induced draft fan is turned on. Due to previous off-cycle operation of the system for a long time, the grates may be blocked, so the fan draws ash (flyash) along with the hot gases. These hot gases while passing through the boiler horizontal firetubes leave flyash materials on the heat transfer surface which reduces its effectiveness, increasing the flue gas temperature and reducing the boiler efficiency. Immediate cleaning of grates is required to improve combustion, reduce heat losses, and increase boiler efficiency.

It was observed that the performance of the McNay wood-fired system improves with increasing system energy load. This system is more efficient at peak load conditions than at average or partial energy load conditions. Fig. 55 shows the relationship of the McNay wood-fired boiler efficiency to system energy load.

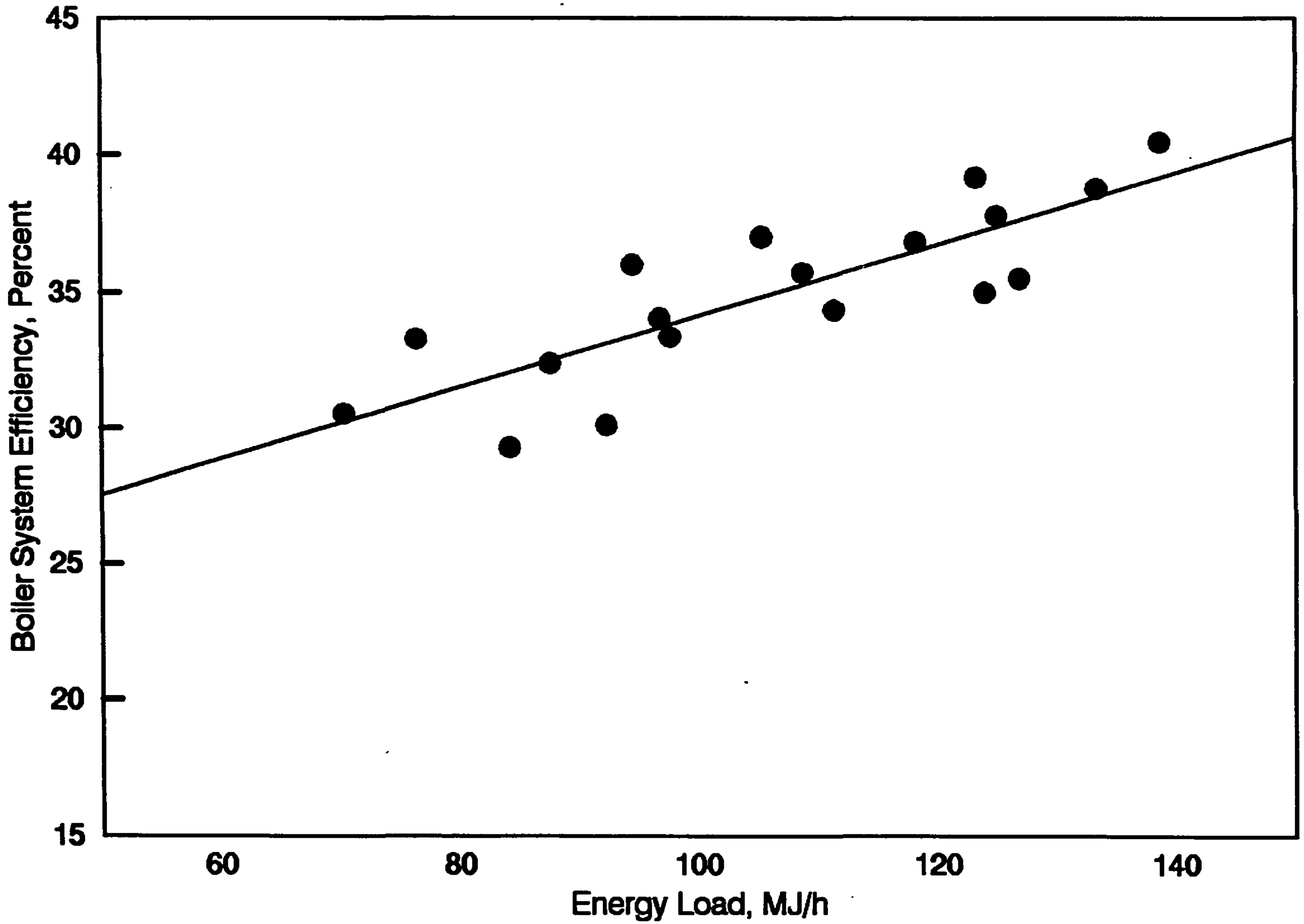


Figure 55. Relationship between energy load and system efficiency

Energy Analysis

Four kind of energy flows can be identified in the McNay integrated wood energy system (Fig. 56). The four basic energy flows are wood energy input, energy from feedback or energy subsidy, energy losses or waste energy, and energy output. These four energy flows are constrained by the thermodynamic laws.

First Law of Thermodynamics (energy conservation):

$$E_{in} + E_{feedback} = E_{out} + E_{waste}$$

Second Law of Thermodynamics (energy degradation): $E_{waste} > 0$

$$E_{in} - E_{waste} = E_{out} - E_{feedback}$$

or Net Yield $= E_{out} - E_{feedback}$

Net gain or net energy ratio $= E_{out} / E_{feedback}$

Sedlik (1978), discussed in detail the theoretical basis for net energy analysis.

Net energy analysis

The energy inputs and losses for each process in the wood energy trajectory are determined by combining process and input-output analysis techniques. Bullard et al. (1978) recommended using a combination of these two techniques to reduce error and to increase accuracy. Baltic and Betters (1983) also used this combined analysis technique in their net energy analysis.

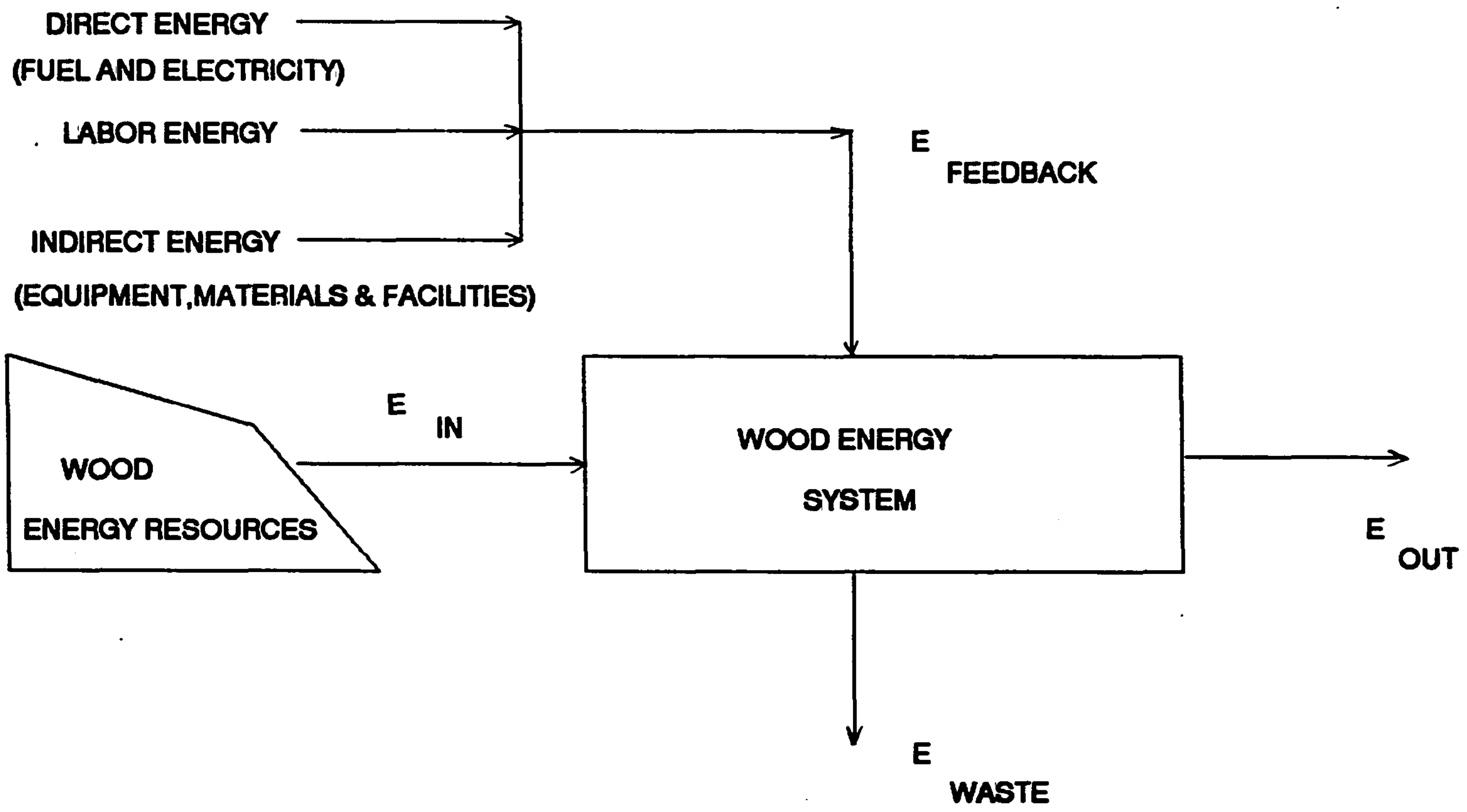


Figure 56. Basic energy flows in a wood energy system

The data used to determine direct energy inputs are actual operating data, collected for all processes in the energy trajectory. Detailed process descriptions of a wood energy trajectory used to calculate energy values are listed in Appendix D. Indirect energy inputs are determined by using energy intensity coefficient data for a 368 - sector model of the entire U.S. economy developed through input-output analysis (Bullard et al., 1978). The energy intensity coefficients are available for the year 1967 and prices are converted to 1967 dollar value by using price indices (deflator) from annual publications of U.S. Bureau of Labor Statistics and the U.S. Bureau of Economic Analysis. Fluck and Baird (1980) discussed the importance of the energy value of labor in agriculture-related net energy analyses. Hall et al. (1986) explained that like any other factor of production, labor has direct and indirect energy costs. Households produce and support human labor just as firms produce capital. Therefore, labor has an energy cost associated with its use. Fluck and Baird (1980) calculated the energy value of U. S. farm labor as 74.25 MJ/h or 594 MJ/day based on food caloric value and the embodied energy of that food (energy consumed to produce food), and a portion of the total lifestyle support energy of the laborer, apportioned between labor and nonlabor or household uses.

In the McNay analysis a labor value of 74.25 MJ per man-hour of energy was used. An example of the methodology to determine energy inputs is presented in Appendix E.

Table 11 summarizes the direct and indirect energy inputs along with labor energy for all the processes in the trajectory. Total energy input for the entire wood energy trajectory is determined as 275,062 MJ for a winter heating season of 3600 hours. About 60% (166,136 MJ) of the energy is consumed in supply processes as compared to 40% (108,926 MJ) of the energy expended in end use processes. Complete energy flows in terms of energy value of wood resources and external and boiler losses for each process within the energy trajectory are illustrated in Fig. 57. The labor, and direct and indirect energy are feedbacks. They are external to the system, and so are designated external losses in the trajectory (Baltic and Betters 1983). In this analysis 40% boiler seasonal efficiency was used while burning green wood chips of 45% moisture on wet basis.

Energy values were normalized to 1000 MJ of delivered or boiler functional energy in this analysis. Because of boiler losses, green wood chips with an energy value of 2500 MJ must be delivered from the supply processes in order to obtain 1000 MJ of functional heat. For each 1000 MJ of functional energy, the external losses of the supply and end use process were calculated as 382 MJ and 251 MJ respectively, leaving 367 MJ of net energy per 1000 MJ of energy

Table 11. Energy inputs for the various processes of the McNay wood energy system for a 3600 hours heating season

	Energy				
	Indirect MJ	Direct MJ	Labor MJ	Maintenance MJ	Total MJ
Supply Process					
Extraction					
Harvesting	618	8,651	13,365	4,512	27,146
Chipping	11,349	54,147	7,425	14,164	87,085
Equip.Transp.	736	18,882	2,970	1,579	24,167
Subtotal	12,703	81,680	23,760	20,255	138,398
Transportation					
Chip Van	3,880	10,825	2,970	4,676	22,351
Unloading	167	3,609	1,485	126	5,387
Subtotal	4,047	14,434	4,455	4,802	27,738
Supply Total	16,750	96,114	28,215	25,057	166,136
End Use Process					
Boiler system	26,543	41,371	12,251	7,616	87,781
Processing	2,633	16,256	-	2,256	21,145
End Use Total	29,172	57,627	12,251	9,872	108,926
TOTAL	45,922	153,741	40,466	34,929	275,062

delivered for space heating. Fig. 58 shows the net energy balance for the entire integrated wood energy trajectory. The net energy ratio or net energy gain was 1000/633 = 1.58.

Net energy sensitivity analysis

Sensitivity analysis examines the relative effect of changes in certain processes in the trajectory on system performance. Table 12 shows the net energy ratios for each process and subprocess based on the 1086,400 MJ wood energy delivered. An overall net energy ratio of 6.54 was determined for the energy delivered from supply process. Table 13 shows the net energy ratios for each process and subprocess of the entire trajectory, based on the 434560 MJ boiler functional heat energy. The overall net energy ratio of 1.58 was determined for the entire trajectory. It is evident from Table 13 that net energy ratios of certain processes are comparatively lower, indicating poorer performance than other processes.

It can be observed from Table 13 that the net energy ratio for the boiler system loss is the lowest (0.667) when compared to other ratios in the trajectory. This low ratio reflects the large boiler energy loss which has drastically reduced the amount of delivered energy. The performance of the system can be improved by reducing boiler energy loss, which in turn depends upon the moisture content of wood chips and efficiency of the boiler system. In this analysis

Table 12. Net energy ratios[a] based on 1086,400 MJ delivered energy for the wood energy trajectory

	Energy			
	Direct	Labor	Indirect	Overall
Supply Process				
Overall	11.30	38.50	25.99	6.54
Extraction	13.30	55.72	32.96	7.85
Harvesting	125.58	81.29	1757.93	40.02
Chipping	20.06	146.32	95.73	12.47
Equip.Transp.	57.54	365.79	1476.09	44.95
Maintenance	-	-	53.64	53.64
Transportation	75.27	243.86	122.77	39.17
Chip Van	100.36	365.79	280.00	48.61
Unloading	301.02	731.58	6505.39	201.67
Maintenance	-	-	226.24	226.24

[a]Net energy ratio = delivered energy/feedback energy

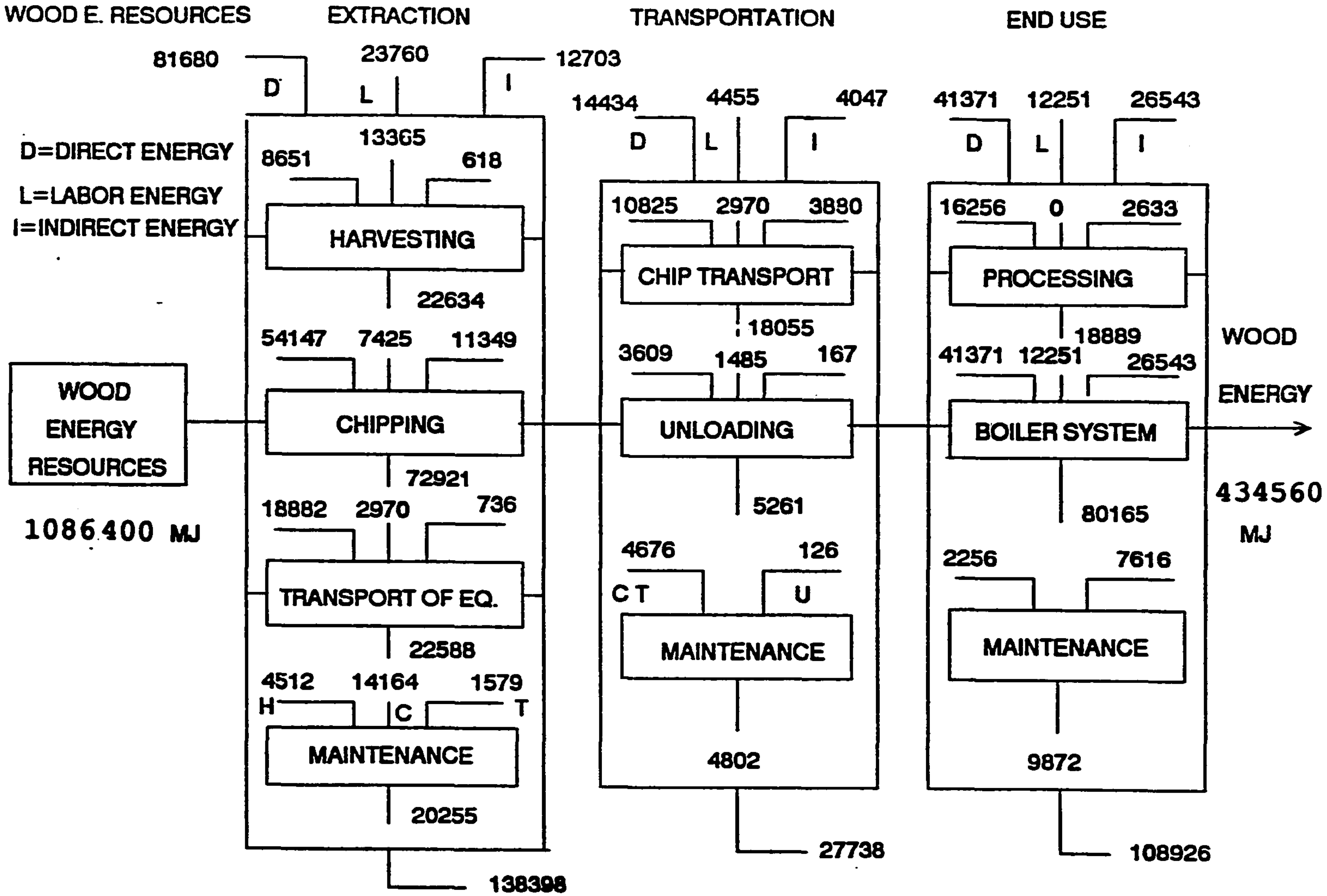


Figure 57. Energy flows, MJ, in the McNay integrated trajectory

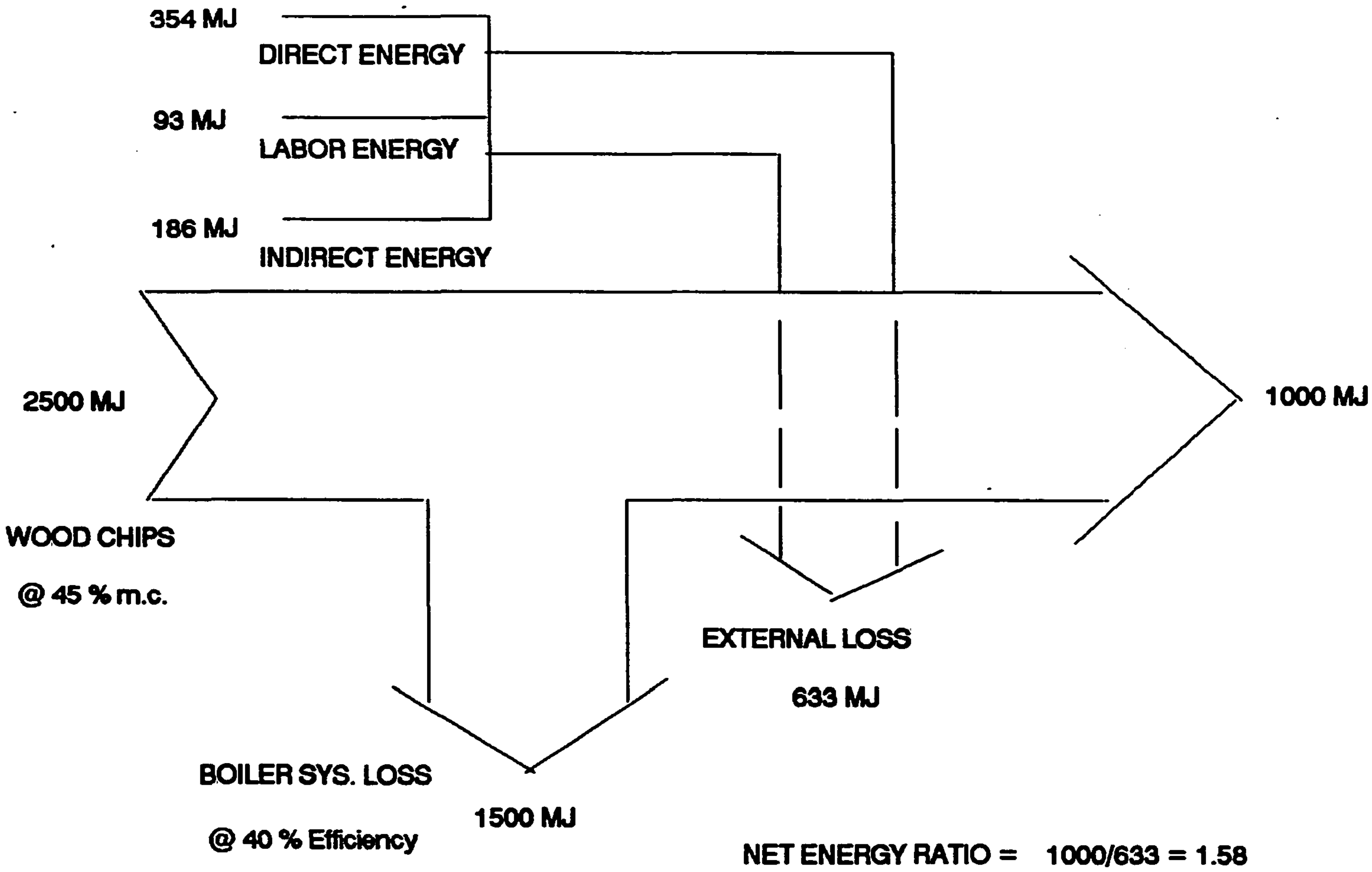


Figure 58. Net energy balance for the integrated wood energy trajectory based on boiler functional heat for efficiency of 40%

boiler efficiency was only 40%. The wood-fired boiler system efficiency can be improved 65 - 70% (Tillman et al., 1981). The boiler system has a larger capacity than necessary and was operated at partial load conditions during the winter heating season. The boiler efficiency can be improved either by increasing the energy load on the system or by replacing it with a smaller capacity boiler that more closely matches the heating energy requirements at the McNay farm. If the functional heat energy of 434560 MJ remains constant, improved boiler efficiency of 65% will reduce the amount of wood chips from 100 tons to 61.5 tons. The boiler energy loss ratio can be improved 179% by increasing the boiler efficiency by 25% (Table 14). The overall net energy ratio of the system would increase 49%, from 1.58 to 2.35, by an improvement in boiler efficiency to 65% (Fig. 59).

Considering all processes in the trajectory, the extraction process and end use process have lower energy ratios than transport process (Table 13). In the extraction process, the chipping requires the most direct operational fuel energy. Table 14 also indicates that along with improvement in the boiler system loss ratio, there are 62% and 31% improvements in the supply and end use processes of the trajectory respectively. Similarly the sensitivity analysis shows that further improvement can be achieved by improving the

Table 13. Net energy ratios[a] based on 434,560 MJ boiler functional heat for the entire wood energy trajectory

	Energy			
	Direct	Labor	Indirect	Overall
<u>Entire Trajectory</u>				
Overall ratio	2.83	10.74	5.37	1.58
Supply Process	4.52	15.40	10.40	2.62
Extraction	5.32	18.29	13.18	3.14
Harvesting	50.23	32.52	703.17	16.01
Chipping	8.02	58.53	38.29	5.00
Equip. Trans.	23.02	146.32	590.44	17.98
Maintenance	-	-	21.46	21.46
Transportation	30.11	97.54	49.11	15.67
Chip Van	40.14	146.32	112.00	19.44
Unloading	120.41	292.63	2602.12	80.67
Maintenance	-	-	90.50	90.50
End Use Point:	7.54	35.47	11.30	3.99
Processing	26.73	-	165.04	20.55
Boiler System	10.50	35.47	16.37	4.95
Maintenance	-	-	44.02	44.02
Boiler System Loss	.0.667			

[a]Net energy ratio = functional energy/feedback energy

Table 14. Net energy sensitivity analysis of boiler system efficiency

	Boiler efficiency				
	40 %	55 %	improvement %	65 %	improvement %
Overall ratio	1.58	2.06	32.0	2.35	49.0
Supply process	2.62	3.60	37.0	4.50	62.0
Extraction	3.14	4.30	37.0	5.10	62.0
Transportation	15.67	21.53	37.0	25.46	62.0
End point process	3.99	4.80	20.0	5.23	31.0
Boiler system loss	0.667	1.22	83.0	1.86	179.0

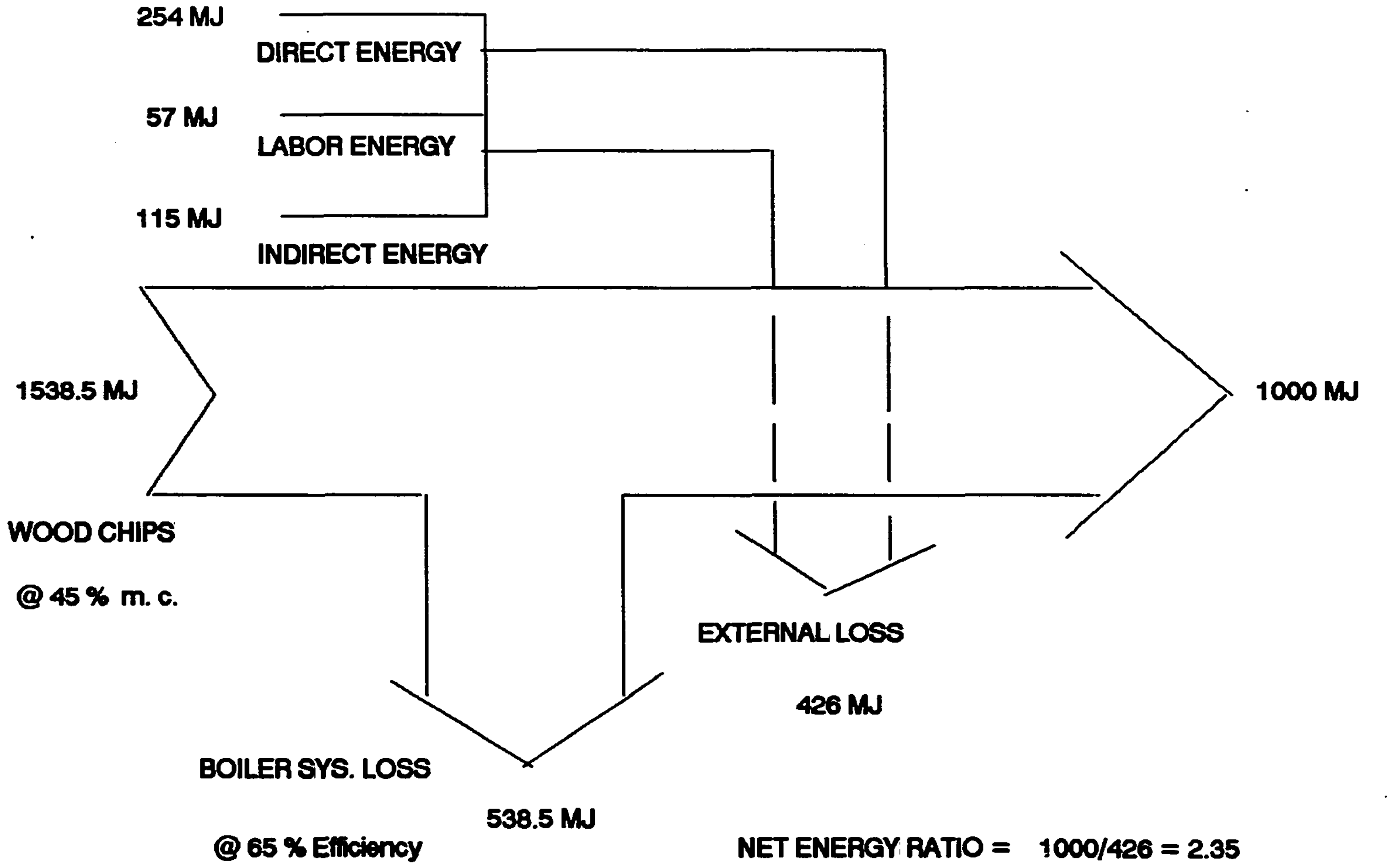


Figure 59. Net energy balance for the integrated wood energy, based on boiler functional heat after improving boiler efficiency of 65%

extraction process and reducing direct energy requirements, as well as by burning drier wood chips.

<u>Net energy comparative analysis</u>

The suitability of an integrated wood energy system can be determined by comparative analysis with conventional fuel systems of the same functional heat capacity designed for space heating. The net energy ratios for conventional fuel systems were calculated using similar methodology, as described in Appendix E. The comparative net energy ratios of both wood fuel and conventional fuel energy systems are shown in Table 15. The McNay integrated wood energy system at 40% efficiency has a lower net energy ratio than the refined petroleum product system (liquified petroleum gas). By improving wood boiler efficiency to 65%, the wood energy system has a 6% better net energy ratio than a refined petroleum product system.

Economic Analysis

The major factors affecting the economics of a wood fired boiler energy system are capital costs, operation and maintenance costs, and wood chip fuel costs, and system efficiency. The cost of wood chip fuel plays a significant role in the economic viability of the wood energy system in comparison with a fossil based system. All the operations for wood energy recovery at the McNay farm are semi-

Table 15. Comparison of net energy ratios of wood energy system vs. conventional system

Energy system	Boiler system efficiency %	Net energy ratio
Natural gas	65	3.47
Refined petroleum prod. (LPG)	65	2.22
Wood fuel[a]	40	1.58
Wood fuel[a]	55	2.06
Wood fuel[a]	65	2.35

[a]Green wood chips at 45% moisture on a wet basis.

mechanized. The operations include the use of existing and purchased equipment and facilities available at the farm, along with human power in all the wood energy recovery processes for space heating. The comprehensive data regarding capital investment and operational costs of various equipment being used for the wood energy system at the McNay farm are presented in Appendix D.

The total costs of wood chip fuel at the McNay farm are the sum of the equipment cost, labor cost and production cost of forest wood. The total cost of wood fuel delivered for energy production was determined to be $76.00 per metric ton. The contribution of equipment cost in the harvesting, chipping, and transportation processes of green wood chip fuel was 37%, labor cost was 50% and land cost was 13%. The fuel energy costs were computed as $6.41/GJ for wood chips and $8.40/GJ for fossil based LPG system (Appendix F). The total life cycle cost of the wood boiler energy system was determined to be $184,820 while burning green wood chips of 45% moisture at 40% boiler seasonal efficiency (Table 16). On the other hand, life cycle cost of the competing fossil (LPG) based system was computed as about $100,400 with boiler seasonal efficiency of 65%. Table 16 also indicates that there is no net saving or payback period for the McNay wood energy system as compared to the LPG system.

Table 16. Life cycle cost analysis of wood energy system and fossil based system

	Wood energy system	Fossil based system
Life period, years	25	25
Present value of investment, $	35,000	10,000
Present value of salvage, $	511	146
Present value of operation and maintenance, $	27,788	40
Present value of fuel energy, $	122,546	90,494
Total life cycle cost, $	184,823	100,388
Net saving, $	- 84,435	
Internal rate of return	NO	
Saving to investment ratio	-2.19	
Payback period	No	

Results from sensitivity analysis

A sensitivity analysis was conducted to determine the relative effects of changes in the cost of wood fuel, boiler seasonal efficiency and cost of LPG in the economic viability of the wood-fired energy system.

Table 17 shows the life cycle cost of the wood energy system at various boiler seasonal efficiencies if potential changes to reduce fuel cost could be adopted. The major parameters in wood fuel costs are equipments cost, labor cost and carrying cost of the wood resources. In the first alternative, the labor cost was eliminated from the fuel cost by considering that the family labor and or permanent labor is available free of cost (off peak work) for the wood energy system. Also, available literature related to forest wood resources in Iowa stated that forest resources are poorly managed and under utilized and that domestic forest wood production can be increased by applying improved management practices and producing energy as an alternate farm crop. Countryman et al. (1985) estimated that in Iowa about 50% of the standing timber per ha should be removed under the improved management practices. So in the second alternative, in addition to labor cost, carrying cost of the natural wood stand is also eliminated. Fig. 60 shows the life cycle cost of the wood energy system at various seasonal efficiencies. The life

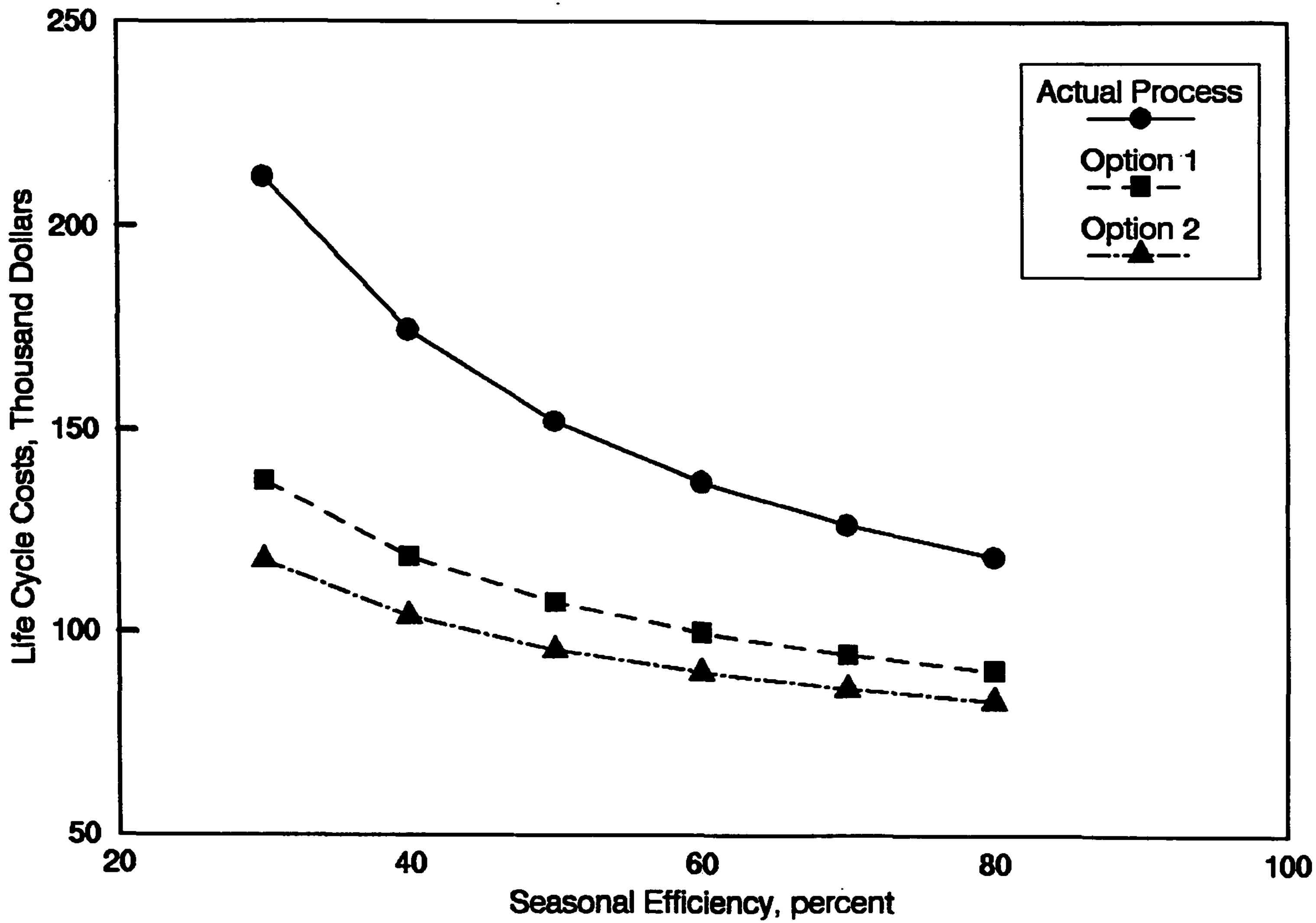


Figure 60. Life cycle cost vs seasonal efficiency of wood energy system with three fuel cost options

Table 17. Sensitivity analysis of life cycle cost of wood energy system at various seasonal efficiencies

Boiler system efficiency, %	Actual process $, thousand	Alternate Option 1 $,thousand	Alternate Option 2 $ thousand
30	225.36	143.95	122.32
40	184.82	123.53	107.31
50	160.30	111.28	98.30
60	143.82	103.11	92.30
70	132.17	97.28	88.01
80	123.43	92.90	84.79

cycle cost of the wood energy system with wood fuel alternatives 1 & 2 are 32% and 41% respectively less than calculated when considering all cost parameters at boiler efficiency of 40% when burning 45% moisture wood chips.

LPG fuel prices can be raised in the analysis due to the fact that LPG prices sometimes increase greatly during the winter heating season in the state of Iowa. Fig. 61 illustrates that at LPG price of $8.4 per GJ ($0.21/l or $0.8/gallon), a net saving for the wood energy system can only be observed in the case of alternatives 1 & 2 when boiler seasonal efficiency increased to 50%. Fig. 62 and Fig. 63 show a life cycle saving for the wood energy system at LPG fuel prices of $10.4/GJ (0.26/l or $1.0/gallon) and $12.4/GJ ($0.32/l or $1.2/gallon) respectively.

The sensitivity analysis revealed that the wood energy system cost for the existing system was only comparable with the LPG system when wood boiler system efficiency increased to 60% and at LPG fuel price of $12.4/GJ (Fig. 63).

It is also evident from the sensitivity analysis that the wood energy system can be made more competitive by burning drier wood chips and by improving efficiencies of the fuel handling system.

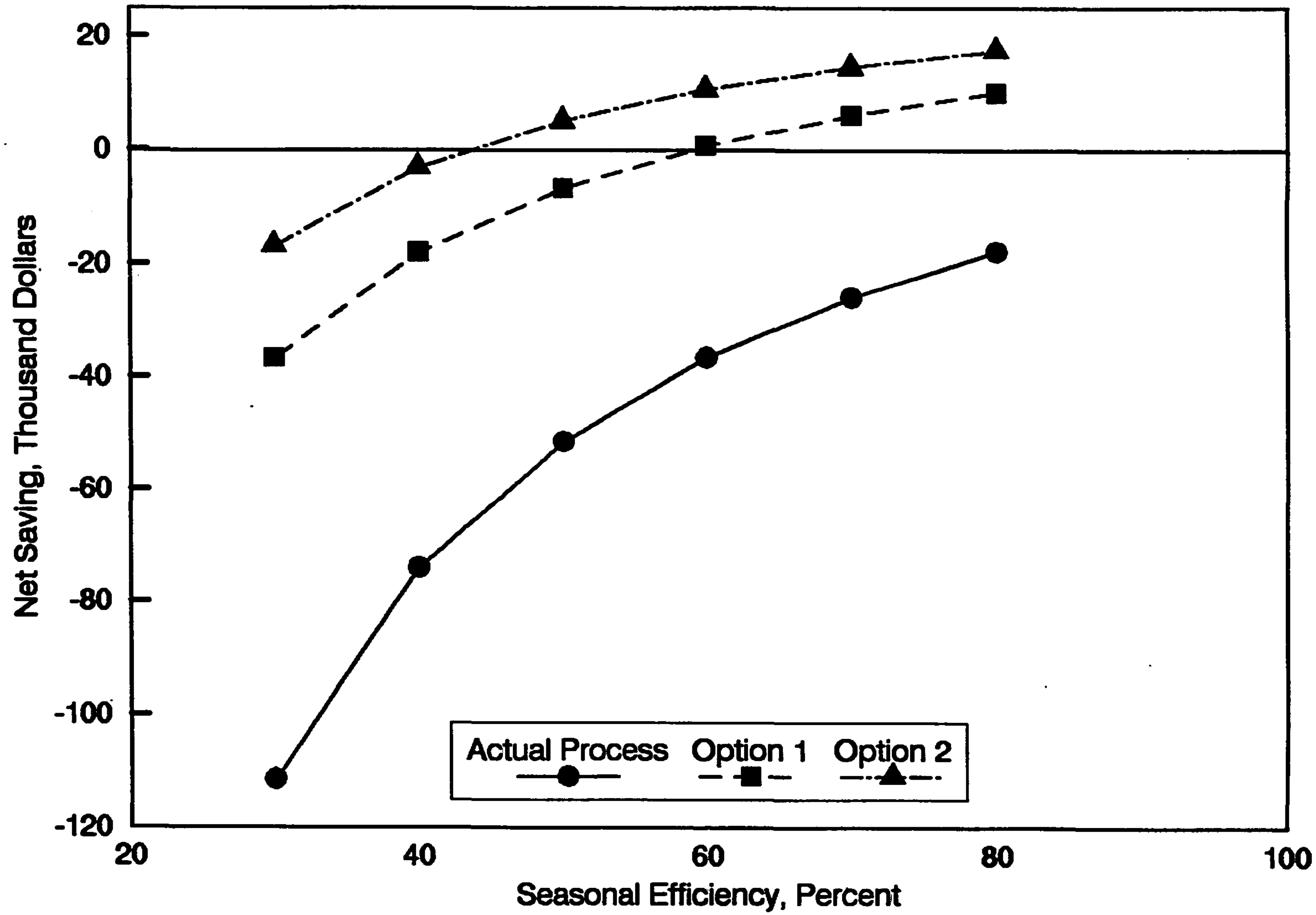


Figure 61. Net saving vs seasonal efficiency of wood energy system with three fuel cost options compared to a compatible system at LPG price $8.4/GJ

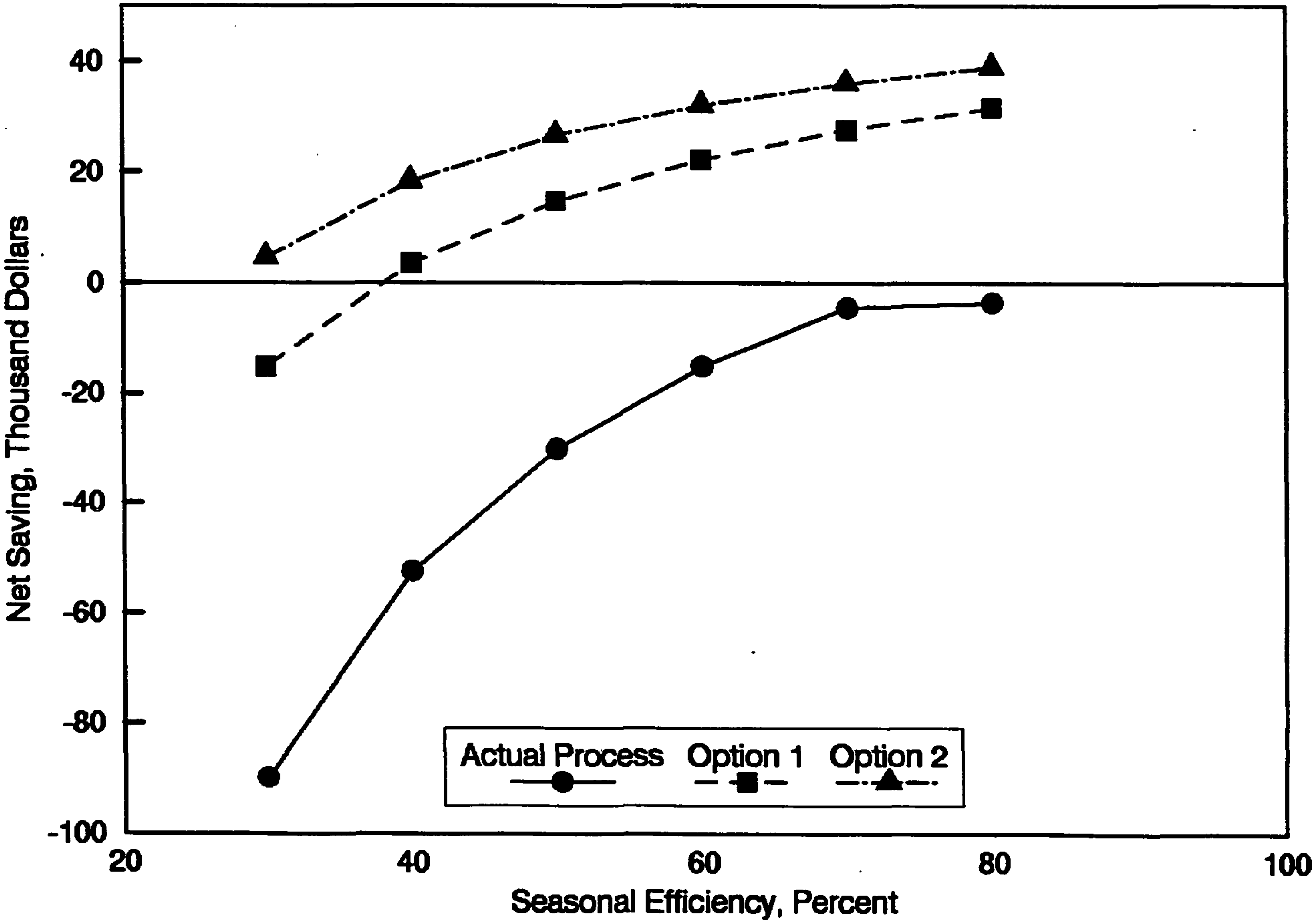


Figure 62. Net saving vs seasonal efficiency of wood energy system with three fuel cost options compared to a compatible system at LPG price $10.4/GJ

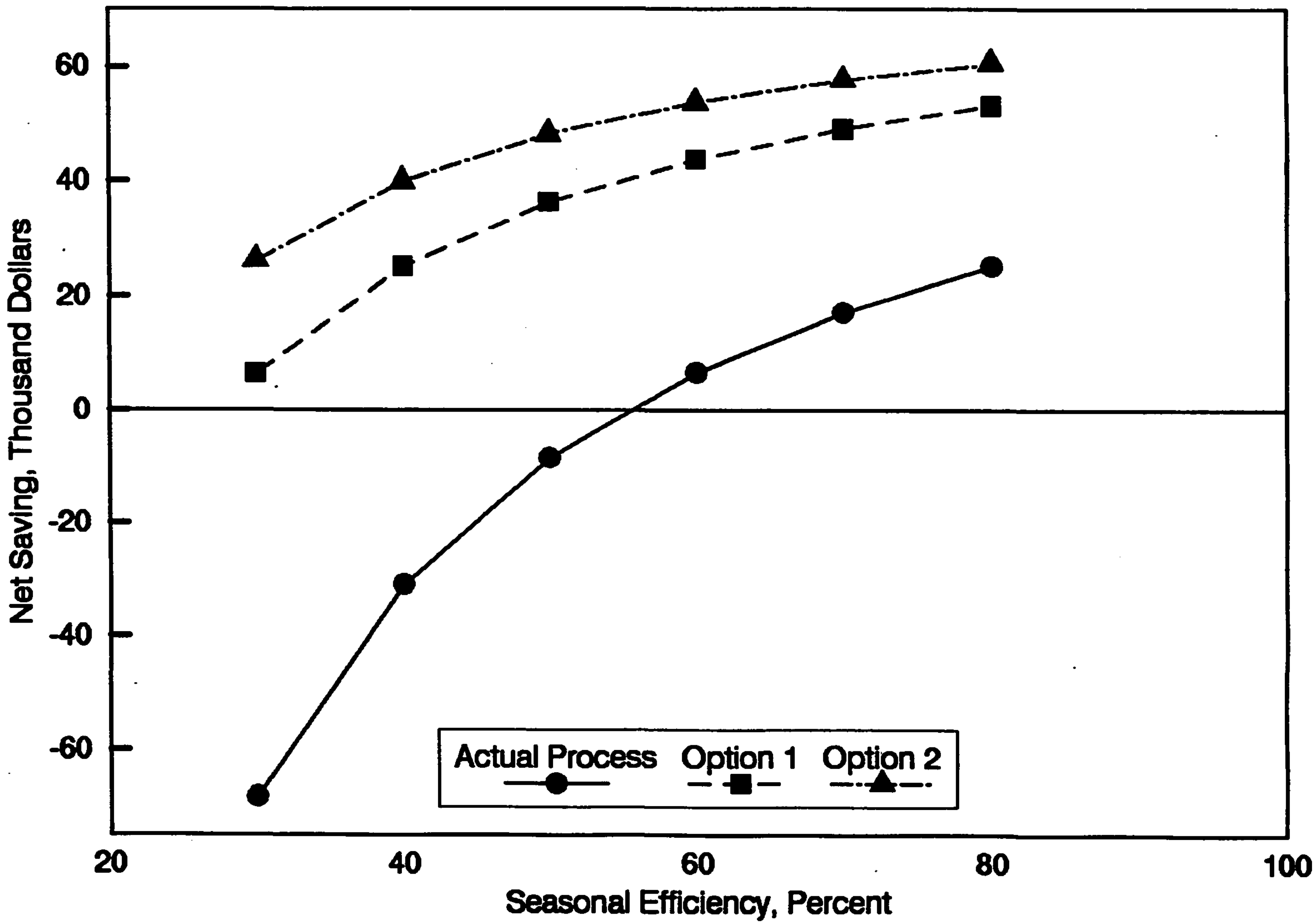


Figure 63. Net saving vs seasonal efficiency of wood energy system with three fuel cost options compared to a compatible system at LPG price $12.4/GJ

Operating Experience with Integrated System

The McNay integrated wood energy system uses on-farm wood energy resources to produce heating energy through a hot water boiler system for farmstead applications. The operating experience with this integrated energy system is presented in six parts as follows:

1. fuel handling
2. ash handling
3. grate and flue cleaning
4. particulate flow and creosote deposits
5. trouble shooting and safety
6. quality of heating and major concerns

Fuel handling

Fuel handling involves all stages from timber harvesting, chipping, transportation, and conveying of wood chips to storage for the boiler system. All fuel handling operations were performed by using both human and mechanical power. Permanent farm labor performed all these fuel handling operations during the off-peak season of the year. Mostly, harvesting and chipping operation were performed once a week. The tractor operated chipper (Valby CH-300) was utilized for making green whole tree chips. The chipper worked smoothly without any major problem for chipping green timber up to

250 mm diameter. The chips were transferred from the chip van into the boiler room storage wagon twice a week during the months of December 1989 and January 1990, and once a week during February and March 1990.

Ash handling

Ash was removed at least once and sometimes twice a week, depending upon the mass of fuel consumed. As an average, 30 - 50 kg of ash was removed weekly from the ash pit. It takes approximately 10 to 15 minutes for ash removal. Ash was applied as a fertilizer on agricultural land at the farm.

Grate and flue cleaning

The grates of the burner need cleaning at least twice a day. It takes about 4 to 5 minutes to clean the grates. As the boiler system was operated under partial load conditions, it caused frequent fuel and ash flowability problem over the grates. During cold days, grates were sometimes cleaned three times a day in order to increase rates of wood fuel combustion.

The flue required cleaning after two to four weeks of continuous boiler operation under the existing conditions. Only flyash particulates were found in the flue, which was scraped clean. About

6 to 8 kg of fly ash was collected from flue, boiler base and other boiler components. It takes about 3-4 man-hours for flue cleaning.

It was observed that immediately after cleaning the flue, the flue gas temperature dropped from 371°C with 14% carbon dioxide to 288°C with 8% carbon dioxide during the optimum-cycle operation mode under steady state conditions. After flue cleaning the dilution of carbon dioxide concentration in flue gas occurred because more oxygen or air could then infiltrate through the various joints of the combustion chamber systems.

It was found that flue cleaning had no significant effect on overall boiler efficiency while operating under partial load conditions. But flue cleaning lowers flue gas temperature and increases oxygen (excess air) concentration in the flue gas flow. It was also observed that the flue gas temperature again approached 371°C with 14% carbon dioxide concentration in the flue gas within 2 to 3 days after flue cleaning during the on-cycle mode of boiler system operation under steady state conditions.

<u>Particulate flow and creosote deposit</u>

The particulate flow, generally is reported to be much lower for wood chip fired boilers than for hog-fired (mostly bark) and sawdust boilers. Particulates such as flyash and inert material are important due to environmental regulatory requirements imposed on wood combustors. Environmental Protection Agency (EPA) regulations are applicable for new wood energy facilities having an output capacity of at least 1.055 million kJ/h (1 million BTU/h) depending on location and surrounding conditions.

The McNay wood boiler system is of one-half the capacity required for particulate concerns under the EPA regulations. Also, the wood energy facility is located on a farm in open atmosphere. This facility burns whole tree wood chips that generate particulate concentration less than 0.08 kg/million kJ under normal operating conditions, compared to EPA allowable particulate emission rate of 0.19 kg/million kJ. Finally, the design of the horizontal firetube boiler system is such that it provides enough time for hot gases within the boiler to drop particulate matter in the flue and boiler base.

The soot deposits and creosote formation in the stack (chimney) and other flue gas passages were frequently checked and no significant amount was found in the stack throughout the boiler operation.

Trouble shooting and safety

No major problem was found with the operation of the wood-fired system throughout the winter season. Initially, the speeds of the fuel transfer conveyor to the boiler feeding hopper and storage wagon auger were mismatched. After these were corrected, the entire integrated wood energy system operated smoothly. The wood-fired boiler system was connected to the existing liquified petroleum gas (LPG) boiler heating system in the house. The LPG boiler piping and baseboard heaters were used for space heating in the house by supplying thermal energy from the wood-fired boiler through the heat exchange unit. Arrangements were made such that in case of any problem with the wood-fired system, the existing LPG system could start immediately to supply thermal energy for space heating in the house.

All safety aspects were duly considered in installing and operating the wood-fired boiler energy system. The wood boiler system was installed separately and away from the farmstead. The operators give diligent attention to all equipment involved in operating the integrated energy system.

Quality of heating and major concerns

From the point of view of the McNay Farm Supervisor living in the house, heating with the wood fired boiler produced the same level of thermal comfort as did the LPG boiler system. The wood energy system was as responsive to the thermostat control as was the LPG system under normal winter conditions.

There were two major concerns with the wood energy system. First, the wood energy system was not able to supply the heat energy requirements under peak winter conditions, when outside temperature was below -18°C (0°F), particularly during the third week of December 1989. The most likely reason for this was that the heat exchanger unit installed in the house to transfer energy from the wood-fired boiler is of low capacity and designed for average winter energy load requirements in the house instead of peak load conditions.

A second major concern was that the boiler system burned substantially more fuel than was originally anticipated. Actually the boiler system is of larger capacity than needed for normal conditions. Operating the system at partial load conditions resulted in increased heat losses from the system and inefficient boiler operation during moderately cold periods.

SUMMARY AND CONCLUSIONS

An integrated biofueled boiler energy system has been recently installed at Iowa State University's McNay Memorial Research Center. The project is provide information to Iowa farmers and small industries concerning the operation of wood-fired energy systems and the management of domestic energy resources for potential substitution for imported heating energy. The McNay integrated wood energy system includes the various processes required to convert wood energy on the ground to energy at the point of actual use for space heating. These include timber harvesting, chipping, transportation and storage of wood chips, and energy recovery by a boiler system, and energy delivery for space heating through an underground insulated piping system and heat exchange units.

The objective of this research was to determine performance characteristics of the wood-fired energy system for space heating for farmstead applications. The intent was to determine and specify the operating conditions that maximize boiler system performance and to monitor the seasonal energy delivered to the farmstead heating system. An energy measuring instrumentation and data acquisition system was developed to collect and record data.

The performance of the wood-fired boiler energy system was measured through a series of 20 tests employing quadratic central composite design. Three independent variables were studied that control the fuel feed rate, amount of combustion air, and strongly influence the dependent variable, the boiler system efficiency (BEFF). The three independent variables were (1) primary air damper (PAD) opening, (2) secondary air damper (SAD) opening, and (3) depth of fuel bed (DFB). The PAD was varied between 51 mm to 119 mm, SAD was varied from 4 mm to 47 mm and DFB was varied from 46 mm to 132 mm.

Analysis of the performance test data indicates that the effects of the independent variables on boiler system efficiency are quadratic rather than linear. Both linear and quadratic effect of these variables on boiler system efficiency are highly significant, whereas cross products or interactions between variables are not significant indicating that these input variables act independently of each other. The quadratic performance prediction equation was determined.

The optimum operating conditions for maximum efficiency were experimentally determined and specified: primary air damper 76 mm (3.0 in), secondary air damper 25 mm (1.0 in), and depth of fuel bed 89 mm (3.5 in). Under these optimum operating conditions, boiler system efficiency was measured to be 54% while burning green wood chips at 45% moisture on a wet basis under steady state conditions. The amount of excess air was determined to be about 39% and the wood chip fuel consumption rate was 40 Kg/hr. The flue gas analysis indicated concentrations of: carbon dioxide 14%, oxygen 6.5%, and nitrogen 79.5%. Carbon monoxide was not detected in the flue gas analysis.

The boiler system was oversized relative to the average farmstead energy load. Three modes or cycles of boiler operation were incorporated into the system. These are partial-cycle, on-cycle or optimum-cycle, and off-cycle. The boiler performance was measured in all 3 modes during extended periods by incorporating optimum input operating conditions. During partial and off-cycle conditions, the boiler system efficiency decreased to 36% and 28% respectively, under steady state conditions.

The boiler system operation was monitored for total energy production delivered for space heating for farmstead applications during winter heating season of 1989-90. The monitoring data consisted of total fuel consumed and thermal energy delivered to the house and workshop in each day, week, month and during the whole winter season. The boiler system consumed about 60.5 metric tons of green wood chips during the winter season of three and a half month from December 16, 1989 to March 31, 1990. Total seasonal energy production delivered to the farmstead for space heating was 60,836 kwh or 219 GJ. Out of this, about two-third of the thermal energy was delivered to the house and one-third was delivered to the workshop.

Several kinds of analysis are needed to plan intelligently the use of renewable energy resources such as wood-biomass for energy production. Two important techniques are net energy analysis and economic analysis using life cycle costs. Both kinds of analyses are used to determine the energy cost of wood energy along with a comparison with fossil based heating systems. The net energy analysis and life cycle cost analysis indicated that the wood energy system for space heating is not strongly viable as compared to a fossil based energy system under existing conditions.

The sensitivity analysis, however, indicated that the wood energy system can be made comparable to fossil based systems by improving system efficiency and reducing the wood fuel handling costs. The seasonal efficiency of wood energy system can be improved to 65%, either by operating the system at peak load conditions or by reducing the capacity of the boiler system combustion chamber. The smaller burner would then operate new peak load conditions.

The major concern about burning too much wood chip fuel can be solved by using a half-sized capacity burner with this boiler under present farmstead energy requirements for space heating.

It can be concluded from this study that the wood-fired boiler energy system is potentially suitable for farmstead applications on farms where large amounts of timber growth go unused annually.

The use of wood-biomass resources for energy production will necessitate some trade-offs of short term benefits for the long term benefits of improved environment and preservation of natural fossil energy resources for future generations.

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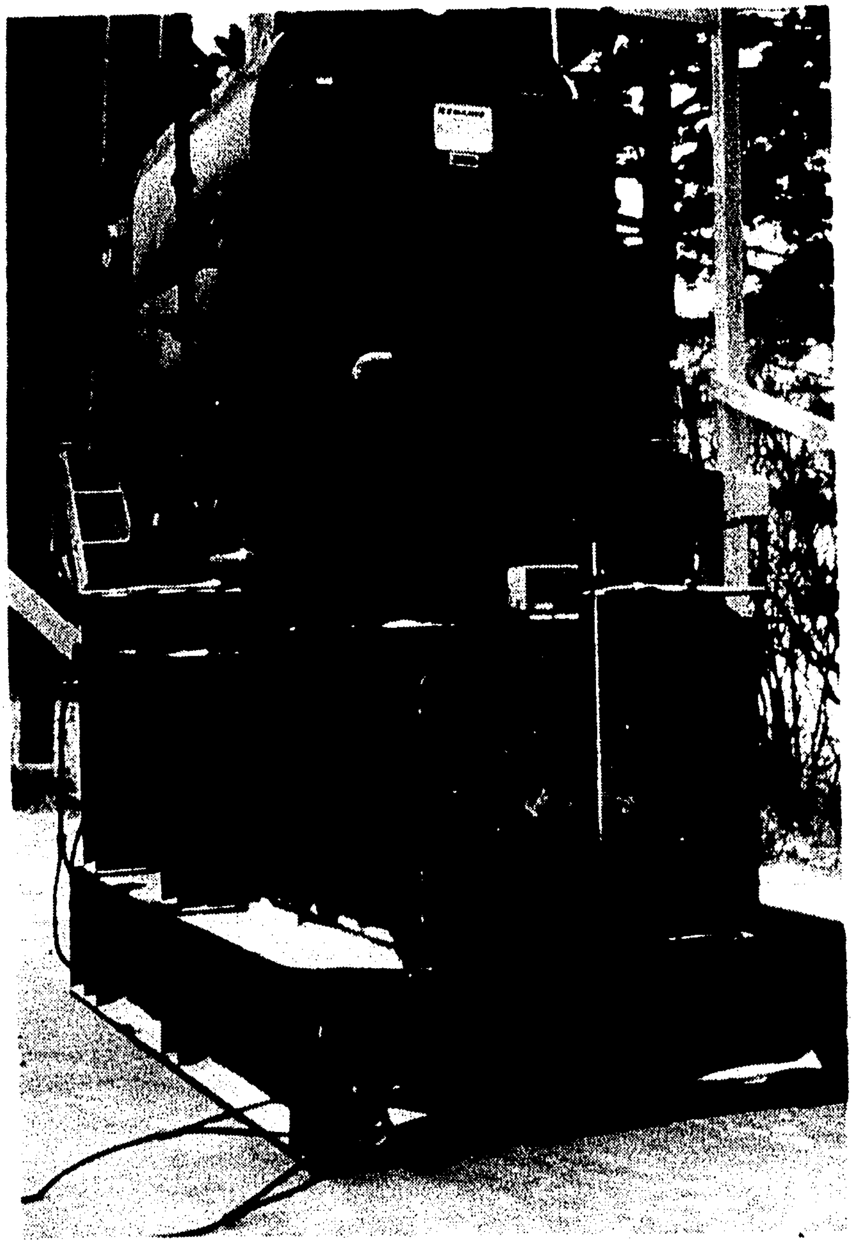
(and continue to provide) love and inspiration needed for this accomplishment - work is proudly dedicated.

APPENDIX A: SPECIFICATIONS OF McNAY BOILER SYSTEM

Manufacturer	:	Energy Resource System, Inc. Roseville, Minnesota.
Model	:	ERS C15 - WC (Fig. 64)
Type	:	Hot water horizontal firetube boiler
Boiler power	:	11.2 BKW (15 BHP)
Design capacity	:	530,000 kJ/h (502,000 BTU/h)
Working pressure	:	207 kpag (30.0 Psig)
Hot water leaving	:	82 °C (180 °F)
Water entering	:	71 °C (160 °F)
Boiler water jacket capacity		550 liters (145 gallons)
Fuel quantity at Design capacity	:	68.64 kg/h (151 lb/h)
Fuel type	:	Green wood chips @ 50 % moisture
Heating surface	:	8.2 m^2 (88 ft^2)
Furnace volume	:	0.62 m^3 (22 ft^3)

Figure 64. ERS C15-WC hot water boiler



APPENDIX B: WOOD-FIRED BOILER PERFORMANCE DATA

The procedures and equations used in boiler efficiency calculations both by the input-output method and the heat loss method are presented in the body of this dissertation. All original data were collected in English Units and were later converted to SI units using appropriate conversion factors. A total of 20 boiler performance tests were conducted under steady state conditions. Table B-1 lists the values of three input variables for each test, and the corresponding measured boiler efficiency. Table B-2 lists the excess air and flue gas temperature for each test. Table B-3 lists the flue gas analysis percent CO_2, O_2 and N_2 for each performance test.

Table B4 - B7 indicate the boiler efficiency, fuel consumption rate, flue gas temperature, and percent CO_2 respectively in three modes of the boiler operation.

The hot water flow rates for the house and workshop were measured 1.38 l/s (21.21 gpm) and 0.47 l/s (7.47 gpm) respectively. These flow rates to the house and the workshop were remained constant throughout the winter season. The fuel consumption rate during performance tests was difficult to measured precisely for each test due to short duration of the test. The boiler efficiency was calculated by using the heat loss method. During extended period testing, all performance parameters were precisely measured and the input-output method was used in the boiler efficiency calculation (Table 9 and Table B-8). An example of boiler efficiency calculation for a performance test, and a extended period test is illustrated as follows:

Example of calculation:

Performance test # 9 (using heat loss method)

Measured data:

Fuel ultimate analysis as-fired, in percent

C	:	27.852
H	:	3.311
O	:	22.957
N	:	0.1375
S	:	0.0
Ash	:	0.7425
moisture	:	45.0
Total	:	100.0

Higher heating value (HHV) = 19752 kJ/kg (on a dry basis)

HHV = 10864 kJ/kg as-fired fuel @ 45 % fuel moisture

Boiler room air temperature = 21 $^{\circ}$C

Boiler room relative humidity = 25 %

Average flue gas temperature = 371 ° C

Flue gas analysis, in percent

CO_2	:	14.0
O_2	:	6.5
N_2	:	79.5
CO	:	0.0

Unburned carbon loss = 3.0 %

Using equation (6):

Theoretical air, WTA = 3.349 kg/kg of as-fired fuel

Using equation (7):

Actual air, WAA = 4.56 kg/kg of as-fired fuel

Using equation (8):

Excess air = [(4.56 - 3.349)/3.349] x 100

= 39.02 %

Using equation (11):

Boiler efficiency (BEFF) = [(HHV - Losses)/HHV] x 100

or

BEFF = (100 - Losses in percentage) x 100

where

Losses = LDG + LMF + LMH + LMA + LUC + LRU + LFD

All these individual boiler system losses are explained in the body of this dissertation. The variables and symbols are also presented in the chapter of nomenclature. Variables and their values used in heat loss equations are given below:

T_{fg} = 371 ° C

T_{ref} = 21 ° C

h_{gG} = 3220.92 kJ/kg

h_{fref} = 88.61 kJ/kg

h_{gref} = 2540.12 kJ/kg

UF = 3.0 %

CB = 27.852 -(3.0/100 X 27.852)

= 27.106 %

H = 3.311 %

W_{md} = 0.0038 kg of water/kg of dry air

C_{pg} = 1 kJ/kg ° C

The individual boiler system losses are as follows:

	Losses in kJ	Losses in percentage
LDG	1607.87	14.8
LMF	1412.32	13.0
LMH	923.44	8.5
LMA	54.32	0.5
LUC	282.46	2.6
LRU	543.20	5.0
LFD	173.83	1.6

Total Losses 4997.44 46.0

Boiler efficiency = [(10864 - 4997.44)/10864] x 100

= 54.0 %

or = (100 - 46/100) x 100

= 54.0 %

Useful heat = 10864 - 4997.44

= 5866.56 kJ (54 %)

Stack loss = LDG + LMF + LMH + LMA + LFD

= 4171.78 kJ (38.4 %)

Radiation loss = 543. 20 kJ (5.0 %)

Ash loss = 282.46 kJ (2.6 %)

Example of calculation:

Extended period test # 10 (using input-output method)

Measured data:

House water supply temperature, T_{SR} = 78.3 ° C

House water return temperature, T_{SR} = 74.0 ° C

Workshop supply temperature, T_{SW} = 76.0 ° C

Workshop return temperature, T_{RW} = 71.2 ° C

House water flow rate, M_{WH} = 1.38 l/s

Workshop water flow rate, M_{WW} = 0.47 l/s

Specific heat of boiler

feedwater, Cp = 3.7 kJ/kg ° C

Fuel consumption rate = 28.1 kg/h

Using equation (9):

Boiler efficiency (BEFF) = Q_{out}/Q_{in}

where

Q_{out} = heat energy delivered

Q_{in} = heat energy input (fuel)

Q_{out} = energy delivered to house + energy delivered to workshop

$$= M_{wH} (h_{2H} - h_{1H}) + M_{wW} (h_{2W} - h_{1W})$$

$$\text{or} = M_{wH} Cp (T_{SH} - T_{RH}) + M_{wW} Cp (T_{SW} - T_{RW})$$

$$= 1.38 \times 3600 \times 3.7 (78.3 - 74.0) +$$

$$0.47 \times 3600 \times 3.7 (76.0 - 71.2)$$

$$= 79040.88 + 30049.92$$

Q_{out} = 109091 kJ/h

or = 109 MJ/h

Q_{in} = (fuel consumption rate) x HHV (1 - M)

= 28.1 x 19752 (1 - 0.45)

= 305267.16 kJ/h

or = 305.3 MJ/h

Boiler efficiency = (109/305.3) x 100

= 35.7 %

Table B-1. Test input operating variables and measured boiler efficiency during performance tests of the wood-fired boiler

Test #	PAD (mm)	SAD (mm)	DFB (mm)	BEFF %
1	51	13	64	48.3
2	51	13	114	51.9
3	51	38	64	50.1
4	51	38	114	52.7
5	102	13	64	50.0
6	102	13	114	53.8
7	102	38	64	50.5
8	102	38	114	54.0
9	76	25	89	53.5
10	76	25	89	54.5
11	76	25	89	54.0
12	76	25	89	54.1
13	76	25	88	53.5
14	76	25	89	55.1
15	33	25	89	50.9
16	119	25	89	53.0
17	76	4	89	52.1
18	76	47	89	51.9
19	76	25	46	48.7

Table B-2. Excess air and flue gas temperature measured during performance tests of the wood-fired boiler

Test #	Excess air %	Flue gas temperature ° C
1	105.3	330.5
2	45.2	360.0
3	82.1	349.0
4	73.2	351.7
5	80.7	354.4
6	51.0	365.0
7	86.9	343.3
8	44.0	370.0
9	39.0	371.1
10	38.9	370.0
11	41.3	368.9
12	39.3	372.2
13	37.9	373.9
14	39.0	371.1
15	121.4	337.8
16	112.4	345.0
17	50.3	367.8
18	76.9	370.0
19	132.0	321.1
20	33.8	375.1

Table B-3. Flue gas analysis measured during performance tests of the wood-fired boiler

Test #	CO_2 %	O_2 %	N_2 %
1	9.5	11.2	79.3
2	12.5	7.5	79.2
3	10.5	11.2	78.3
4	11.5	9.5	79.0
5	10.6	10.8	78.6
6	13.0	6.8	80.2
7	10.5	10.9	78.6
8	13.4	6.8	78.8
9	14.0	6.5	79.5
10	14.0	6.6	79.4
11	13.8	6.8	79.4
12	14.0	6.4	79.6
13	14.1	6.3	79.6
14	14.0	6.5	79.5
15	8.8	11.3	79.9
16	9.2	10.5	80.3
17	13.0	7.2	79.8
18	11.0	9.5	79.5
19	8.3	12.7	79.0
20	14.5	6.2	79.3

Table B-4. Boiler efficiency measured during three modes of operation of wood-fired boiler

	Partial-cycle %	Optimum-cycle %	Off-cycle %
	35.0	53.5	28.0
	34.0	52.5	28.5
	36.0	56.0	27.5
	37.5	54.0	27.5
	38.0	54.5	27.5
	37.5	55.0	27.0
	36.5	53.0	28.5
	36.0	53.5	29.5
	35.0	54.0	29.0
	35.5	54.0	28.0
	35.5	55.5	28.0
	36.0	52.5	27.5
	35.5	53.0	29.0
	35.0	54.0	27.0
	36.5	52.0	26.5
	37.0	56.0	28.0
	35.0	54.0	27.5
	36.0	54.0	28.0
	36.5	55.0	29.0
	38.0	55.5	28.5
Mean	36.1	54.07	28.0

Table B-5. Fuel consumption rate measured during three modes of operation of wood-fired boiler

	Partial-cycle kg/h	Optimum-cycle kg/h	Off-cycle kg/h
	26.5	40.0	13.5
	25.0	40.0	12.5
	24.0	38.0	12.5
	24.5	37.0	13.0
	23.5	39.0	13.5
	24.0	42.0	13.0
	26.5	38.0	12.5
	27.0	42.0	13.0
	25.5	43.0	13.0
	25.0	40.0	13.0
	25.0	38.0	12.5
	24.0	41.0	12.0
	25.5	40.0	13.0
	25.5	39.0	14.0
	25.0	38.0	12.5
	25.0	44.0	13.5
	24.0	42.0	13.0
	26.0	41.0	12.5
	25.0	39.0	13.5
	25.0	42.0	13.0
Mean	25.07	40.15	12.92

Table B-6. Flue gas temperature measured during three modes of operation of wood-fired boiler

	Partial-cycle ° C	Optimum-cycle ° C	Off-cycle ° C
	265.5	368.0	210.0
	260.0	370.0	206.0
	254.5	363.0	205.0
	250.0	374.0	195.0
	271.0	378.0	198.0
	268.0	371.0	203.0
	260.0	376.0	204.0
	262.5	371.0	204.0
	257.0	375.0	208.0
	253.0	370.0	204.0
	248.0	368.0	200.0
	260.0	360.0	196.0
	255.0	371.0	199.0
	268.0	365.0	206.0
	263.0	373.0	207.0
	260.0	371.0	202.0
	258.0	370.0	205.0
	260.0	377.0	204.0
	265.5	373.0	208.0
	268.0	371.0	210.0
Mean	260.32	370.8	203.7

Table B-7. Carbon dioxide measured in flue gas during three mode of operation of wood-fired boiler

	Partial-cycle %	Optimum-cycle %	Off-cycle %
	4.5	14.0	2.5
	4.4	14.5	2.4
	4.2	13.0	2.3
	4.0	12.5	2.6
	4.3	15.0	2.8
	4.1	14.5	2.7
	4.0	14.0	2.5
	4.2	14.0	2.7
	4.5	13.5	2.7
	4.3	15.0	2.8
	4.4	14.5	2.8
	4.0	14.0	2.4
	4.4	14.5	2.5
	4.3	13.5	2.5
	4.3	13.5	2.5
	4.2	14.0	2.7
	4.5	14.0	2.8
	4.3	14.0	2.6
	4.2	13.5	2.4
	4.0	14.5	2.8
Mean	4.25	14.00	2.60

Table B-8. House and workshop hot water supply and return lines temperature measured during extended performance testing

Supply Temp.		Return Temp.		Energy	Boiler Jacket		Test time	Energy stored Q_{out}	Net House
Shop °C	House °C	Shop °C	out °C	MJ/h	Start °C	End °C	h	MJ/h	MJ/h
84.4	80.4	82.1	77.6	70.38	80.5	80.5	3.25	0.00	70.38
84.0	82.0	81.4	77.3	76.46	80.0	80.0	3.15	0.00	76.46
83.5	80.2	80.5	75.5	84.31	79.5	79.5	3.35	0.00	84.31
83.4	81.1	80.3	76.8	83.88	73.1	78.9	3.10	+3.85	87.73
74.9	72.5	71.3	68.6	89.86	71.2	75.1	3.05	+2.63	92.49
80.1	77.6	76.5	73.1	92.63	71.1	74.1	3.00	+2.07	94.70
84.3	82.3	80.5	77.8	96.95	75.0	75.0	3.75	0.00	96.95
83.8	81.9	80.3	77.1	93.82	74.0	80.8	3.50	+3.98	97.80
86.1	83.7	81.8	79.2	105.48	78.0	78.0	3.46	0.00	105.48
78.3	76.0	74.0	71.2	108.90	77.0	77.0	3.00	0.00	108.90
80.2	77.9	75.9	72.6	111.53	77.0	77.0	3.28	0.00	111.53
75.4	75.7	70.8	68.1	130.82	83.2	65.5	3.00	-12.5	118.32
74.0	72.1	69.7	66.6	113.39	67.8	82.9	3.10	+10.0	123.39
76.6	74.2	71.6	68.6	124.09	74.0	74.0	3.15	0.00	124.09
77.5	78.4	73.7	71.1	115.44	64.4	79.2	3.15	+9.68	125.12
79.4	76.3	74.2	71.1	127.04	75.0	75.0	3.12	0.00	127.04
78.4	75.9	72.9	70.0	133.49	74.5	74.5	3.01	0.00	133.49
77.3	75.5	71.5	70.1	138.74	75.0	75.0	3.10	0.00	138.74

APPENDIX C: STATISTICAL ANALYSIS

The quadratic central composite design was employed to experimentally determine which independent operating factor values optimize a boiler system efficiency (BEFF). Three independent variables primary air damper (PAD) opening, secondary air damper (SAD) opening and depth of fuel bed (DFB) were chosen for this study and a series of 20 performance tests were conducted. The configuration of this statistical design is shown in Fig. 37. Table 5 listed the level of each independent variable both in original and coded form. Tests of the treatment combinations were performed in random order.

The general linear model (GLM) procedure and response surface regression (RSREG) procedure of Statistical Analysis Software (SAS) were used to analyze the test data and to find the parameters of the quadratic model. The parameters in the model are estimated by least-square regression using the following statements:

For GLM procedure

```
PROC GLM;
MODEL BEFF = PAD SAD DFB
             PAD*SAD PAD*DFB SAD*DFB
             PAD*PAD SAD*SAD DFB*DFB;
```

For RSREG procedure

```
PROC RSREG;

MODEL BEFF = PAD SAD DFB/LACKFIT;
```

The results from GLM procedure and RSREG procedure are presented in Table C-1 and C-2 respectively. It was found from the GLM procedure that the linear effect of SAD was not significant. The results from the RSREG procedure show that the lack of fit is also not significant.

By holding SAD at the optimum value, grid points for PAD and SAD are generated to plot the response surface. PROC RSREG procedure was used to compute the predicted values, which were printed and plotted using contour feature of PROC Plot (Fig. 32).

Table C-1. Results from general linerar model (GLM) for analysis of effects of PAD, SAD, and DFB on BEFF

Dependent Variable: BEEF

Source	DF	Sum of Squares	Mean Squares	F Value	PR>F
Model	9	72.10	8.01	26.03	0.00
Error	10	3.07	0.30		Root Mse
Corrected Total	19	75.18			0.55

Source	Df	TYPE I SS	F VALUE	PR>F	
PAD	1	5.71	18.56	0.00	
SAD	1	0.61	1.99	0.18	
DFB	1	36.94	120.00	0.00	R-SQUARE
PAD*PAD	1	6.27	20.40	0.00	
SAD*SAD	1	6.87	22.33	0.00	0.95
DFB*DFB	1	14.85	48.26	0.00	
PAD*SAD	1	0.44	1.45	0.25	
PAD*DFB	1	0.17	0.58	0.46	
SAD*DFB	1	0.20	0.67	0.43	

Parameter	ESTIMATE	T For Ho: Parameter=0	PR > 1-1	STD ERROR OF ESTIMATE
Intercept	21.99	6.00	0.00	3.66
PAD	0.21	4.63	0.00	0.46
SAD	0.36	4.27	0.00	0.08
DFB	0.33	6.88	0.00	0.04
PAD*PAD	-0.00	-5.62	0.00	0.00
SAD*SAD	-0.00	-5.41	0.00	0.00
DFB*DFB	-0.00	-6.95	0.00	0.00
PAD*SAD	-0.00	-1.20	-.25	0.00
PAD*DFB	0.00	0.76	0.46	0.00
SAD*DFB	-0.00	-0.82	0.43	0.00

Table C-2. Results from response surface regression (RSREG) for analysis of effects of PAD, SAD, and DFB on BEFF

Response Surface for Variable BEFF					
Response Mean	52.32				
Root MSE	0.55				
R-Squar	0.95				
COEF of variation	0.01				
Regression	DF	TYPE I SS	R-SQUARE	F-RATIO	PROB
Linear	3	43.26	0.57	46.85	0.00
Quadratic	3	28.01	0.37	30.33	0.00
Crossproduct	3	0.83	0.01	0.90	0.47
Total Regression	9	72.10	0.95	26.03	0.00
Residual	DF	SS	Mean Square	F-Ratio	PROB
Lack of Fit	5	1.16	0.23	0.60	0.70
Pure Error	5	1.91	0.38		
Total Error	10	3.07	0.30		
Parameter	DF	ESTIMATE	STD DEV	T-RATIO	PROB
Intercept	1	21.99	3.66	6.00	0.00
PAD	1	0.21	0.04	4.63	0.00
SAD	1	0.36	0.08	4.27	0.00
DFB	1	0.33	0.04	6.88	0.00
PAD*PAD	1	-0.00	0.00	-5.62	0.00
SAD*PAD	1	-0.00	0.00	-1.20	0.25
SAD*SAD	1	-0.00	0.00	-5.41	0.00
DFB*PAD	1	0.00	0.00	0.76	0.46
DFB*SAD	1	-0.00	0.00	-0.82	0.43
DFB*DFB	1	-0.00	0.00	-6.95	0.00
Factor	DF	SS	Mean Square	F-Ratio	PROB
PAD	4	16.05	4.01	13.04	0.00
SAD	4	10.30	2.57	8.37	0.00
DFB	4	52.18	13.04	42.38	0.00

Solution for Optimum Response

Factor	Critical Value
PAD	88.19
SAD	25.19
DFB	110.38

Predicted Value at Optimum 54.96

Eigenvalues	Eigenvectors PAD	SAD	DFB
-0.00	0.931	-0.11	0.34
-0.00	-0.35	-0.03	0.93
-0.00	0.09	0.99	0.07

Solution was a maximum

APPENDIX D: EQUIPMENT ENERGY COST DATA

Wood Resources

Wood type: Fresh harvest from natural timber stand

Wood fuel HHV: 10.864 MJ/kg @ 45 % moisture

Total wood chips required: 100 metric tons

Heating Season : 5 months (3600 hours)

(Nov. 1, - March 31)

Table D-1. Names of equipment and parameters used in Tables D-2 and D-3

CS	:	Chain saw (2 units are used in harvesting operation)
CHP	:	Chipper
TR1	:	Tractor # 1
TR2	:	Tractor # 2
TR3	:	Tractor # 3
PUT	:	Pickup truck
CV	:	Chip van
CON	:	Conveyor

Parameters are as follows:

A	:	Purchase price, thousand dollars
B	:	Year of purchase
C	:	Equipment life, years
D	:	Salvage value, thousand dollars
E	:	Annual potential use of machine, hours
F	:	Annual use for wood chip fuel handling
G	:	Fractional use of equipment for wood chip fuel handling
H	:	Repair and maintenance cost, % of purchase price for 100 hours use
I	:	Diesel consumption, l/h (price $ 0.32/l)
J	:	Gasoline consumption, l/h (price $ 0.28/l)
K	:	Labor, man-hours

Table D-2. Supply process equipment data

Equip.	Parameters										
name	A	B	C	D	E	F	G	H	I	J	K
CS	0.44	1988	10	-	2.0	90	0.45	2.5	-	1.13	180
CHP	11.0	1988	10	1.1	5.0	100	0.20	1.5	-	-	100
TR1	40.0	1989	10	4.0	10.0	100	0.10	1.2	11.35	-	-
TR2	25.0	1986	10	2.5	10.0	60	0.08	1.2	3.78	-	-
TR3	1.0	1980	10	0.1	5.0	20	0.15	1.2	3.78	-	-
PUT	3.5	1988	10	0.35	4.0	40	0.10	1.2	-	11.35	40
CV	2.0	1988	10	-	4.0	60	0.15	1.2	-	-	40
CON	0.9	1988	10	-	10.0	20	0.02	1.2	-	-	20

Table D-3. End use process equipment data

Equipment name	Parameters				
	A	B	C	H	K
Boiler system	33.8	1988	25	1.2	165
Feed conveyor	1.2	1988	25	5.5	-
Storage wagon	2.0	1988	25	2.5	-

APPENDIX E: ENERGY CALCULATIONS FOR CHIPPING PROCESS

The methodology used to calculate energy inputs is illustrated as follows:

The chipper is operated by tractor PTO power, thus the tractor is considered as an integral part of the chipper. Direct energy inputs of fuel and labor energy are determined from actual process data collected during operation of the chipper. Values are listed in Appendix D.

Indirect energy inputs of equipment and materials are calculated using energy intensity coefficient data for the U.S. economy developed through input-output analysis (Bullard et al. 1978). Energy intensity coefficients were available for year 1967, so 1967 was considered as a base year for this analysis. The energy coefficients for various sectors of the U.S. economy are calculated at their producer price, not at consumer price. The prices of chipper and tractor are adjusted by subtracting trade and transport margins. Bullard et al. (1978) developed the values for trade and transport margins for all BEA (Bureau of Economic Analysis) sectors and corresponding SIC (Standard Industrial Classification) codes. The total energy expended in the chipping operation was calculated to 87,085 MJ's, as presented in Table E-1.

Table E-1. Total energy expended in chipping operation for McNay integrated wood energy system

Kind of energy invested	Machine		
	Chipper		Tractor
<u>Indirect energy</u>			
BEA sector	48.03		44.00
SIC codes	3553		3522
Energy invested, MJ	3,409.04		7,940.36
Total indirect energy, MJ		11,349.40	
<u>Maintenance energy</u>			
BEA sector	75.0		75.0
Energy invested, MJ	3,722.23		10,441.87
Total maintenance energy, MJ		14,164.10	
<u>Direct fuel energy</u>			
BEA Sector			31.01
Operational Fuel energy, MJ		54,146.66	
<u>Labor energy</u>			
Labor input energy, MJ		7,425.00	
Total energy expended in chipping, MJ		87,085.16	

APPENDIX F: ECONOMIC PARAMETERS FOR McNAY INTEGRATED WOOD ENERGY SYSTEM

Farmstead seasonal energy load	=	441,000 MJ (441 GJ)
HHV of wood chip fuel @ 45 % moisture content	=	10.864 MJ/kg
HHV of LPG fuel	=	25.0 MJ/l
Wood boiler system efficiency	=	40 %
LPG boiler system efficiency	=	65 %
Life of energy system	=	25 years

Cost of Wood Chip Fuel

<u>Actual Process</u>

Considering all cost factors:

Equipment cost in wood fuel handling	=	28.0 $ per metric ton
Carrying cost of forest wood	=	10.0 $ per metric ton
Labor cost, 3.8 man-hrs/ton @ 10/h	=	38.0 $ per metric ton
Total wood chip fuel cost	=	76.0 $ per metric ton
Wood chip fuel energy cost	=	(76.0 $/ton)/(10864 MJ/ton)
	=	0.007 $/ MJ
or	=	7.00 $/million kJ (7.0 $/GJ)
Seasonal or annual wood energy cost	=	(7.00 $/GJ)441 GJ
	=	3,087.0 $
or	=	3,087 $ / 0.4 BEFF
	=	7,717.5 $
Present worth of wood energy cost (25 years)	=	122,546 $

<u>Alternate option 1</u>

Excluding labor cost:

Total wood fuel cost	=	38.0 $ per metric ton
Wood chip energy cost	=	3.5 $ /million kJ (3.5 $/GJ)

<u>Alternate option 2</u>

Excluding labor and carrying cost:

Total wood fuel cost	=	28.0 $ per metric ton
Wood chip energy cost	=	2.58 $/million KJ (2.58 $/GJ)

Cost of LPG Fuel

Cost of LPG fuel	= 0.21 \$/l
LPG energy cost	= (0.21 \$/l)/(25 MJ/l)
	= 0.0084 \$/MJ
or	= 8.40 \$/million kJ(8.40 \$/GJ)
Seasonal or annual LPG fuel energy cost	= (8.40 \$/GJ)441 GJ
	= 3,704.4 \$
or	= 3,704.4 \$/0.65 BEFF
	= 5,699.08 \$
Present worth of LPG fuel energy cost (25 years)	= 90,494 \$